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REPORT OCEANOGRAPHY No. 74, 2023

Oxygen Survey in the Baltic Sea 2022

- Extent of Anoxia and Hypoxia, 1960-2022

Front: A full water sample tray ready to be used. SMHI sample a large number of water parameters to monitor the marine environment. The laboratory steppers are filled with reagents for preparation of oxygen and hydrogen sulphide water samples. Photo by Martin Hansson during the SMHI June cruise in 2022.

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Oxygen Survey in the Baltic Sea 2022
- Extent of Anoxia and Hypoxia, 1960-2022

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Summary

In 2011 SMHI published the Report Oceanography No 42 with a climatological atlas of the oxygen status in the deep water of the Baltic Sea in 2011. Subsequently, annual updates have been released as new data have been reported to the International Council for the Exploration of the Sea (ICES) data centre. This report provides an update for 2021 and presents the preliminary results for 2022. The oxygen data for 2022 were collected from various sources, including international ICES coordinated trawl surveys, national monitoring programmes, and research projects involving Poland, Estonia, Latvia, Denmark, Sweden, and Finland.

For the autumn period, each profile in the dataset was analyzed for the occurrence of hypoxia (oxygen deficiency) and anoxia (total absence of oxygen). The depths of onset of hypoxia and anoxia were then interpolated between sampling stations to produce two surfaces that represent the depths at which hypoxic and anoxic conditions are present, respectively. The volume and area of hypoxia and anoxia were then calculated and the results transferred to maps and diagrams to visualize the annual autumn oxygen situation during the analyzed period.

The updated results for 2021 and the preliminary results for 2022 show that the severe oxygen conditions in the Baltic Proper after the regime shift in 1999 continues. Levels of anoxia increased somewhat compared to the results for 2020, while the extent of hypoxia remained largely unchanged 2021 but increased in 2022. The increase in anoxia was seen in the southern Baltic Proper and in the Gulf of Finland. In 2021 anoxia was found at 21% of the bottom areas and 31% suffered from hypoxia. Preliminary results for 2022 show that anoxia affected 21% of the bottom areas and 34% suffered from hypoxia. The concentration of hydrogen sulphide is extremely high in all the basins around Gotland. In the Eastern and Western Gotland Basin hydrogen sulphide in the bottom water has reached levels not recorded before. The inflows that occurred during 2021 - 2022 did only affect the oxygen situation in southern parts of the Baltic Proper. No inflows reached the deeper basins around Gotland.

Sammanfattning

I SMHI rapporten Oceanography nr 42 publicerades en klimatologisk atlas över syresituationen i Östersjöns djupvatten år 2011. Sedan dess har årliga uppdateringar släppts när nya data har rapporterats till International Council for the Exploration of the Sea (ICES) datacenter. Denna rapport ger en uppdatering för 2021 och presenterar preliminära resultat för 2022. Syredata för 2022 samlades in från olika källor; internationella ICES-koordinerade trålundersökningar, nationella övervakningsprogram och forskningsprojekt med deltagande från Polen, Estland, Lettland, Danmark, Sverige och Finland.

Under höstperioden analyserades varje profil i datamängden för förekomst av hypoxi (syrebrist) och anoxi (total frånvaro av syre). Djupet där hypoxi respektive anoxi först påträffades interpolerades sedan mellan provtagningsstationer för att producera två ytor som representerar djupen där hypoxiska respektive anoxiska förhållanden förekommer. Volymen och ytan för hypoxi och anoxi beräknades sedan och resultaten överfördes till kartor och diagram för att visualisera syresituationen under hösten under den analyserade perioden.

De uppdaterade resultaten för 2021 och de preliminära resultaten för 2022 visar att de allvarliga syreförhållandena i Östersjön efter regimskiftet 1999 fortsätter. Utbredningen av anoxi ökade något jämfört med resultaten för 2020, medan omfattningen av hypoxi i stort sett förblev oförändrad 2021 men ökade 2022. Ökningen av anoxi observerades i södra Östersjön och i Finska viken. År 2021 påträffades anoxi på 21% av bottnarna och 31% drabbades av hypoxi. Preliminära resultat för 2022 visar att anoxi påverkade 21% av bottnarna och 34% drabbades av hypoxi. Extremt höga svavelvätehalter, de högsta som påträffats, noterades i både Västra och Östra Gotlandsbassängen. De inflöden som inträffade 2021-2022 påverkade enbart de södra delarna av Egentliga Östersjön. Inga inflöden nådde de djupare delarna omkring Gotland.

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1 Background

The central deep regions of the Baltic Proper have a long-standing history of low oxygen levels, which are a natural consequence of the sea's topography, being almost entirely enclosed and having a "fjordlike" shape. The narrow straits and shallow sills in the Belt Sea and Sound allow only limited water exchange between the Baltic Sea and the North Sea.

Moreover, the large catchment area surrounding the Baltic Sea produces substantial freshwater runoff, and the general flow direction through the Sound and Belt Sea is out of the Baltic Sea and into the Kattegat and North Sea. Only specific wind, weather, and sea level conditions cause the flow direction to reverse, allowing inflows to occur. These inflows, which are rare, can transport large amounts of oxygenated and highly saline water into the Baltic Sea. Due to the differing densities of low and high saline waters, stable stratification develops, preventing ventilation of the deep water. Organic matter degradation consumes the available oxygen in the deep water, leading to critical oxygen concentrations for higher marine life or even creating completely oxygen-free conditions.

However, large inflow events or series of small inflows, can supply the deep water of the Baltic Proper with dissolved oxygen, as inflowing water from the North Sea is usually well-oxygenated. The high salinity and density of the inflowing water either form a layer that follows the sea floor or is interleaved at intermediate depths, depending on its density. Inflows can only reach the deep basins of the central basin in the Baltic Proper if the volume is large enough to move over the sills between the different basins of the Baltic Proper, and the density is high enough to settle the inflow along the bottom. Major Baltic Inflows (MBI) are rare, with the latest large MBI occurring as a series of large inflows during 2014-2016 [Volker 2018].

The oxygen situation in the Baltic Proper has become increasingly problematic because large inflows don't occur every year and due to large nutrient inputs over time, mainly between the 1950s and the late 1980s, resulting in escalating eutrophication with increasingly severe symptoms to the Baltic Sea's ecosystem [HELCOM, 2018]. The more organic matter that is supplied to the deep water, the more oxygen is consumed, resulting in oxygen deficiency and if the bottom water is not renewed this will escalate to anoxia. Anoxia is the condition when all oxygen has been consumed by microbial processes, and no oxygen is left in the water. If the water stays anoxic for an extended period, hydrogen sulphide (H_2S) is formed, which is toxic to all higher marine life. Only bacteria and fungi can survive in a water environment with total absence of oxygen.

The pool of hydrogen sulphide found in the deep parts of the Baltic Proper must be oxidized by oxygen-rich inflowing water or pushed above the permanent stratification where oxygen is available before a new inflow can have any effect on the oxygen concentrations. During anoxic conditions, sediments release nutrients such as phosphate and silicate to the water column, which, due to vertical mixing or upwelling events, can reach the surface layer and the photic zone. High concentrations of nutrients in surface waters favour phytoplankton growth, especially cyanobacteria during summer, which can further enhance oxygen depletion as the bloom sinks to the bottom and consumes oxygen when it is decomposed - a vicious circle has formed [Vahtera et al. 2007].

These natural factors, combined with external human pressures on the Baltic Sea, form the basis for the increasingly problematic low-oxygen conditions and the "dead zones" or oxygen minimum zones (OMZ) found in the Baltic Sea. Total absence of oxygen and oxygen deficiency in the deep water or at intermediate depths throughout the year are mainly found in the central deep basins in the Baltic Proper and the Gulf of Finland. Seasonal lack of oxygen is generally found in the southern parts of the Baltic Proper.

Oxygen depletion or hypoxia occurs when dissolved oxygen falls below the level needed to sustain most animal life. The concentration at which animals are affected varies broadly. Literature studies [Vaquer-Sunyer & Duarte, 2008] shows that the sublethal concentration ranges from 0.06 ml/l to 7.1 ml/l. The mean for all experimental assessments was 1.8 +/- 0.12 ml/l. The same study also suggests that the commonly used threshold for acute hypoxia around 2.0 mg/l (1.4 ml/l) is below the empirical sublethal and lethal oxygen concentrations for half of the species tested.

The dominant demersal fish population in the Baltic Sea, the Baltic cod (*Gadus morhua*), has been shown to avoid oxygen concentrations below 1 ml/l [Schaber et al., 2012]. However, already at 4.3 ml/l the condition and growth of cod starts to be affected [Chabot and Dutil,1999]. It has also been shown that Baltic Sea cod eggs need at least 2 ml/l oxygen for successful development [MacKenzie et al., 2000; Nissling, 1994; Plikshs et al., 1993; U.S. EPA, 2003; U.S. EPA, 2000,]. With this background the limit of acute hypoxia, in this report, is set to 2.0 ml/l.

This report presents a time series of the areal extent and water volume of anoxic and hypoxic autumn conditions of the Baltic Proper, including the Gulf of Finland and the Gulf of Riga, for the period 1960 to 2022. The time series were first published in 2011 and the results have been updated annually as new additional data have become available at International Council for the Exploration of the Sea (ICES) [ICES, 2009]. In the report from 2011 and in newly published article a distinct regime shift in the oxygen situation in the Baltic Proper was found to occur around 1999 [Hansson et al, 2011; Almroth et al., 2021]. During the first regime, 1960-1999, hypoxia affected large areas while anoxic conditions were found only in minor deep areas. After the regime shift in 1999, both areal extent and volume of anoxia have been constantly elevated to levels that only occasionally have been observed before 1999.

The report includes maps of bottom areas affected by oxygen deficiencies during 2021 and 2022. The complete and updated time series from 1960 can be found as figures in this report and as maps in Appendix 2, which can be used as a climatological atlas describing the historical development and the present oxygen situation in the Baltic Proper.

2 Data

2.1 Oxygen data

The oxygen data used for the analysis of 2022 are based on oxygen data collected during the annual trawl surveys coordinated by the ICES in the Baltic Sea and North Sea; The Baltic International Acoustic Survey (BIAS), International Bottom Trawl Survey (IBTS) and Polish Multiannual Fisheries Data Collection Programme complemented by data from national and regional marine monitoring programmes and mapping projects with contributions from Finland, Estonia, Latvia, Poland, Denmark and Sweden.

These data have not been fully quality controlled; only preliminary checks have been performed. The time series and the results presented for 2022 will be updated when additional data are reported to ICES in 2023/2024. In this report the results for 2021 has been updated with all available bottle and low resolution CTD data retrieved from the dataset on ocean hydrography at ICES (http://www.ices.dk, last access: 2023-02-09).

Data from the trawl surveys are well suited for concurrent oxygen surveys because of randomized sampling and since cruises are performed by different countries almost simultaneously. Hence, almost all parts of the offshore Baltic Proper are monitored with a vast spatial distribution providing a synoptic view of the oxygen situation. The surveys are also performed during the late summer/autumn period, August to October, when the oxygen situation usually is most severe. Consequently, this is an essential contribution of oxygen data, complementing the regular national and regional monitoring performed monthly at fixed stations.

2.2 Inflow data

The inflow through the Belt Sea and the Sound to the Baltic Sea is an important factor influencing the oxygen development in the deep water in the southern and central basins of the Baltic Proper.

SMHI calculates the flow through the Sound based on the sea level difference between two sea level gauges situated in the northern part (Viken) and the southern part (Klagshamn) of the Sound [Håkansson et. al. 1993, Håkansson 2022]. The results, as accumulated inflow, from 1977 to present are presented in Swedish at the SMHI website under the title "Vattenåret". To improve the yearly summary of inflow/outflow events the calculations has been revised. Inflow/outflow events are added together but small inflows/outflows, < 0.5 days and <1 km^3, that would interrupt and ongoing inflow/outflow, has been added or removed from inflow/outflow events to get at better overview of the size and duration of inflow and outflow events. For the years 2021 and 2022 see Figure 5 and 6 for accumulated inflow and inflow/outflow events [SMHI, 2023].

Another estimate of the flow through the Sound and the Belt Sea has been presented by [Volker 2018]. Simplified, the calculations are based on the mean sea level at Landsort and river discharge to the Baltic Sea. In Figure 1, the two estimates of the flow through the Sound are compared. The results from the two calculations are generally similar and in the same range. The results by [Volker 2018] is usually higher but the SMHI inflows are often divided into several inflow events. Larger inflows seem to correlate better. However, there are some inflows in both time series that do not correlate at all. For example, during late 1980s and 1990s in [Volker 2018] and in early 1990s in the SMHI timeseries. The difference could be explained by the local [SMHI, 2023] and regional [Volker, 2018] perspectives of the two methods.

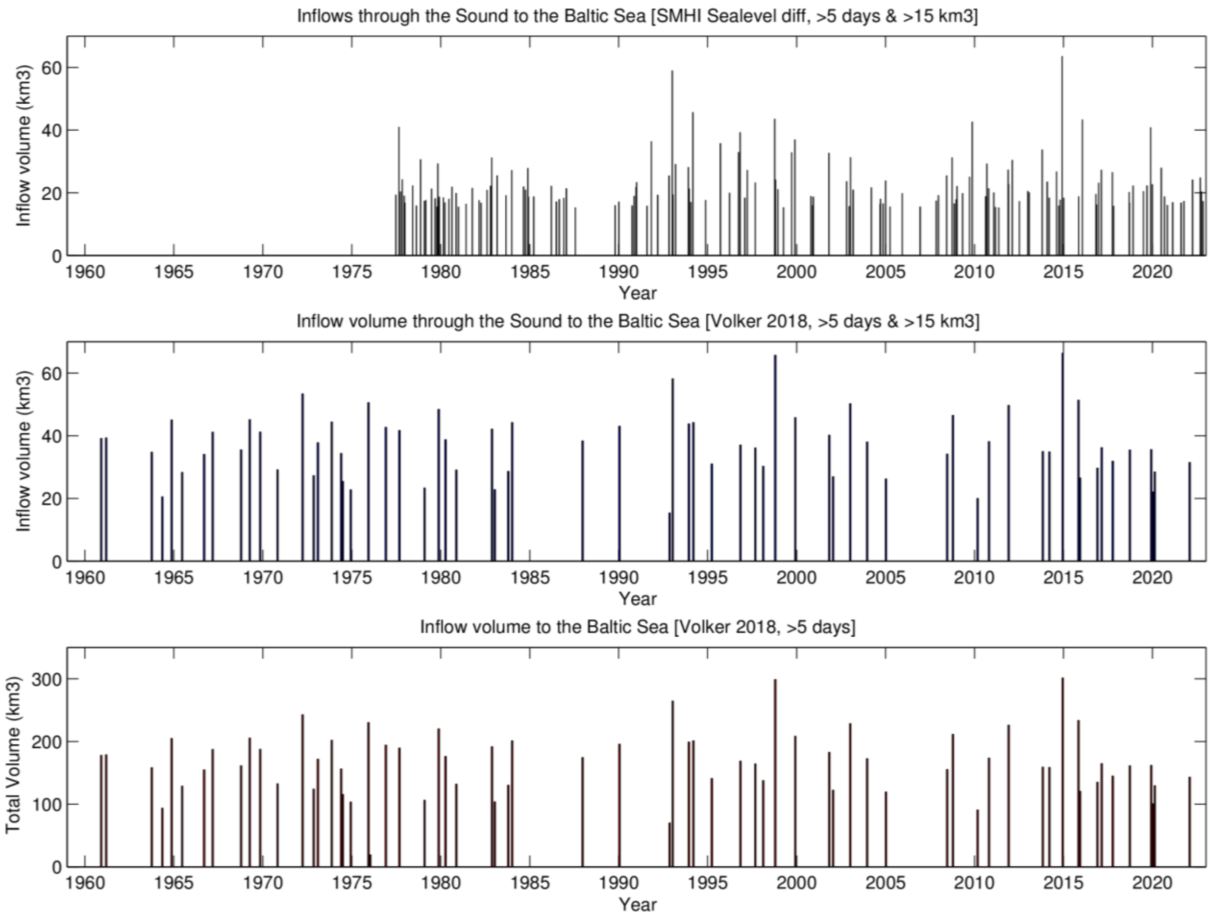

Figure 1. Two different estimations of inflow to the Baltic Sea through the Sound (Öresund). Top: Inflow through the Sound estimated from 1977-2023 by SMHI. [Revised summary of inflow events, SMHI, 2023]. Middle: Inflow through the Sound 1960-2021 estimated by [Volker, 2018]. Bottom: Total volume transport through the Sound and the Danish Straits to the Baltic Sea for inflows, 1960-2022 [Volker 2018]. Note that the time series from [Volker 2018] has not been updated with data after 2022, and the SMHI results are only available from 1977 to present.

3 Method

For the late summer and autumn period, August to October, each vertical profile including at least three data points, was examined for the occurrence of hypoxia (<2 ml/l) and anoxia (<0 ml/l). To find the depth of the onset of hypoxia and anoxia in each vertical profile, interpolation between discrete measurements in the profile was used. If hypoxia or anoxia was not found in the profile, the two deepest measurements in the profile were used to linearly extrapolate the oxygen concentration down towards the bottom. If two or more profiles were found at the same position an average profile was calculated for that position. To process the dataset a few profiles had to be filtered out: for example, when data was missing in the deep water, when correct data from a shallow area obviously negatively affects the interpolation results in nearby deep areas or when questionable data were found.

The depths of the onset of hypoxia and anoxia were gridded with linear interpolation (Delaunay triangulation) between sampling stations, producing a surface representing the depth at which hypoxic and anoxic conditions are found. The surface was compared with bathymetry data, [Seifert, 2001] see Figure 2, to exclude profiles where the hypoxic and anoxic depths were greater than the actual water depth. After filtering the results, the affected area and volume of hypoxia and anoxia was calculated for each year.

The calculations do not account for the existence of oxygenated water below an anoxic or hypoxic layer. Hence, during inflow situations when an intermediate layer with low oxygen concentrations or hydrogen sulphide can be found above oxygenated water, the method overestimates the area and volume. However, these oxygenated zones are still problematic for most benthic animals and fish since they are trapped below an anoxic or hypoxic layer that also prevents migration and recolonization. On the other hand, the oxygenated zones below the intermediary layer, does influence the sediment to water nutrient exchange [Hall et al., 2017 and Sommer et al., 2017].

Areal extent and volumes are presented in relation to the area and volume of the Baltic Proper, including the Gulf of Finland and the Gulf of Riga, see Figure 2 [Fonselius, 1995].

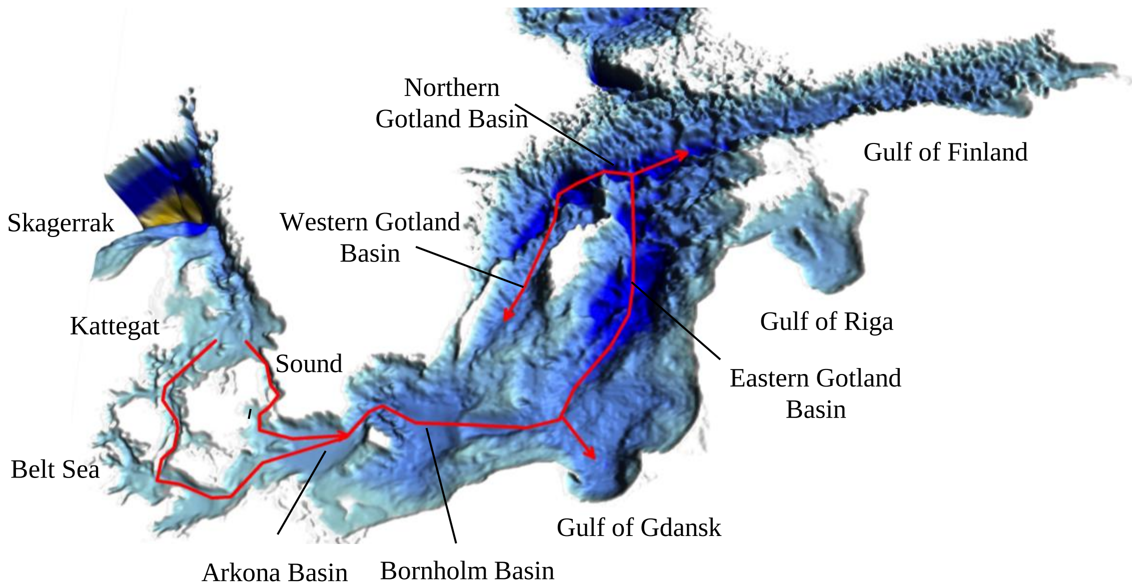

Figure 2. Bathymetry [Seifert, 2001] of the south Baltic Sea and pathways of inflowing deep-water during inflows. The Baltic Proper includes the Arkona Basin, the Bornholm Basin, the Gulf of Gdansk, the Gulf of Riga and the Eastern-, Western- and Northern Gotland Basin [Fonselius, 1995].

4 Result

Extent and volume affected by hypoxia and anoxia during the period 1960 - 2022 are presented in Figures 3 and 4, respectively. Maps presenting bottom areas affected by hypoxia and anoxia during the autumn period 2020 and 2022 can be found in Appendix 2. The mean, max and min areal extent and volume affected by hypoxia and anoxia before and after the regime shift in 1999 [Hansson et. al, 2011]) and the preliminary results for 2022 are presented in Table 1.

The preliminary results for 2022 are the highest noted during the analysed period 1960-2022. However, a large area in the south east Baltic Proper is marked as anoxic but measurements in this area are sparse and the results in this area are therefore uncertain. The update that will be done during next year will hopefully add more measurements in this area to correct or to confirm the results for 2022.

Table 1. Mean, max and min areal extent and volume of anoxia and hypoxia before and after the regime shift. Results are given as part (%) of the area and volume of the Baltic Proper, including the Gulf of Finland and the Gulf of Riga. Updated table from Hansson et. al., 2011.

in %	1960 – 1998		1999 – 2021		2022 (Preliminary)	
	Hypoxia	Anoxia	Hypoxia	Anoxia	Hypoxia	Anoxia
Mean Areal extent	22	5	29	16	34	21
Max Areal extent (Year)	27 (1970)	14 (1969)	33 (2018)	24 (2018)	-	-
Min Areal extent (Year)	9 (1993)	1 (1994)	25 (1999)	10 (2000)	-	-
Mean Volume	13	2	19	9	21	13
Max Volume (Year)	19 (1965)	8 (1969)	22 (2019)	15 (2018)	-	-
Min Volume (Year)	5 (1993)	0.1 (1994)	15 (2000)	4 (1999)	-	-

Areal extent of hypoxia and anoxia

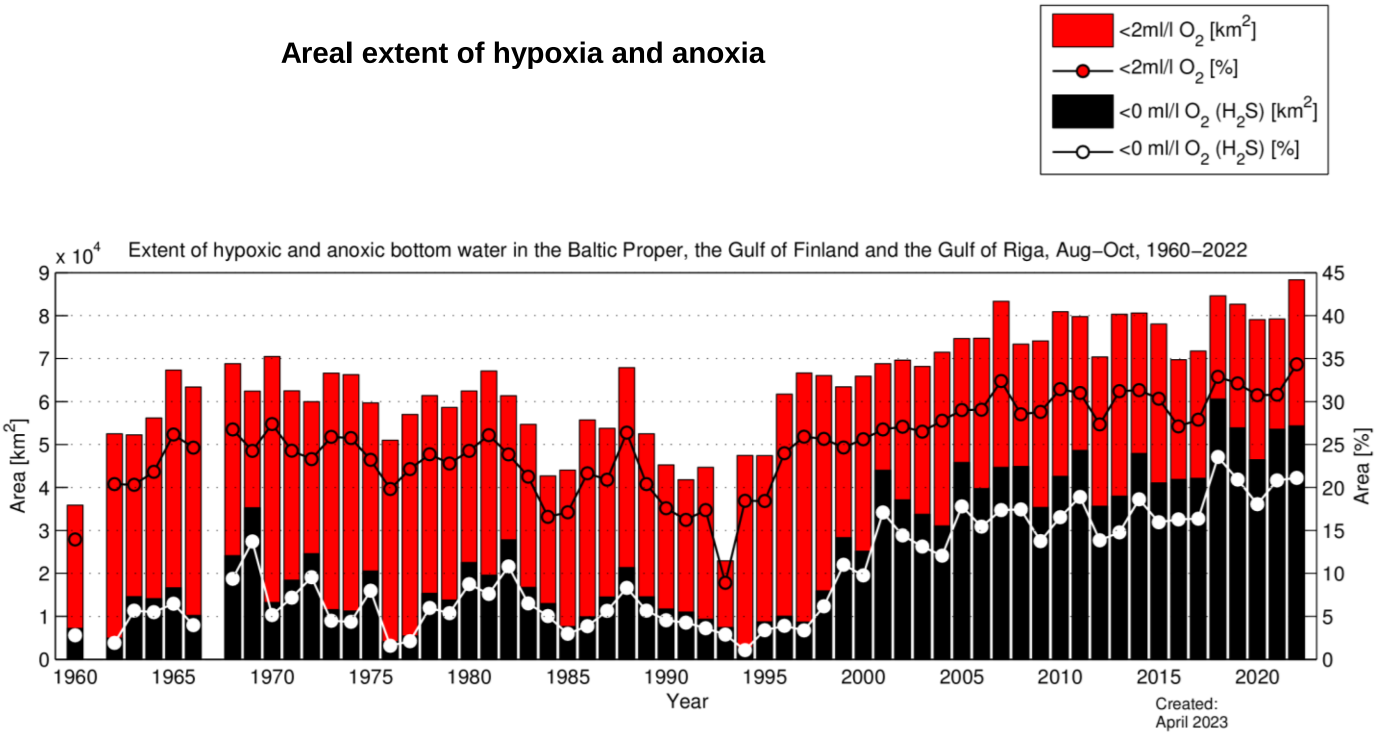

Figure 3. Areal extent of anoxic and hypoxic conditions in the Baltic Proper, Gulf of Finland and Gulf of Riga. Results from 1961 and 1967 have been removed due to lack of data from the deep basins.

Water volume affected by hypoxia and anoxia

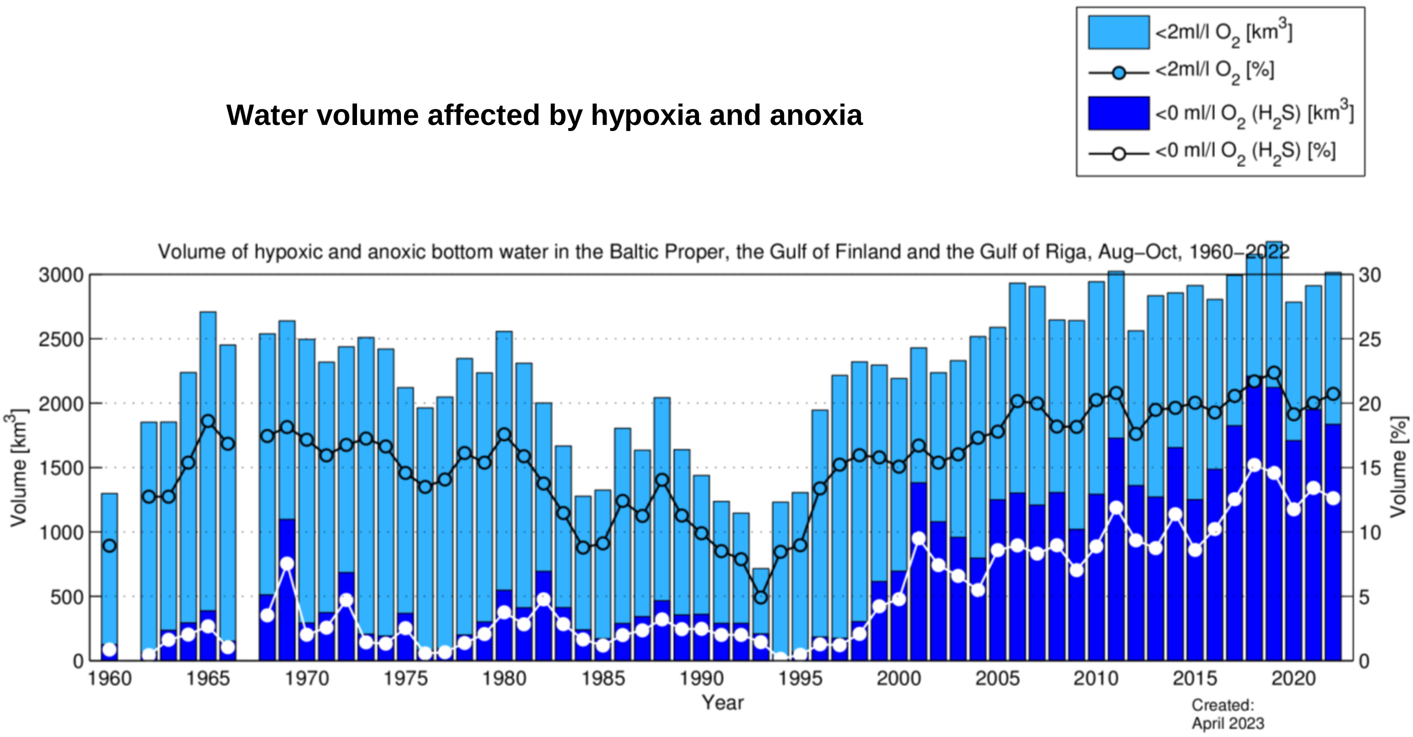

Figure 4. Volume of anoxic and hypoxic deep water in the Baltic Proper, Gulf of Finland and Gulf of Riga. Results from 1961 and 1967 have been removed due to lack of data from the deep basins.

4.1 Updated results for 2021

The result for 2021 has been updated as additional hydrographic data from 2021 has been reported to ICES. After the update the anoxic area increased in the Bornholm Basin and in the outer parts of the Gulf of Finland. There were also some changes in the south east areas of the Baltic Proper and around the Gulf of Gdansk, both increase and decrease. Overall the update resulted in minor changes to the total areas and volumes of both anoxia and hypoxia.

The proportion of areas affected by anoxia increased from 18% to 21% while the hypoxic areas was unchanged at 31%. Small changes were also noted on the affected volumes. For anoxia the proportion of volume affected increased from 11% to 13% and for hypoxia from 18% to 20%.

The results for 2021 are all above the mean for the period after the regime shift in 1999, see Table 1. Hence, the areal extent and volume of anoxia and hypoxia continues to be elevated and the oxygen development in the Baltic Proper that has prevailed since the regime shift in 1999 continues, see Figure 3-4.

Three inflow events through the Sound, with volume larger than 15 km^3 and that last for more than 5 days, occurred in 2021. All inflows were around 15-20 km^3 and occurred in February, August and October.

The total inflow to the Baltic Sea through the Sound during 2021 was 285 km^3 which is lower than normal (compared to the time period 1977-2020 with mean 319 km^3). The outflow was 632 km^3, which is bigger than normal (mean 623 km^3). The accumulated inflow through the Sound (Öresund) during 2021, compared to the mean inflow 1977-2020 can be seen in Figure 5.

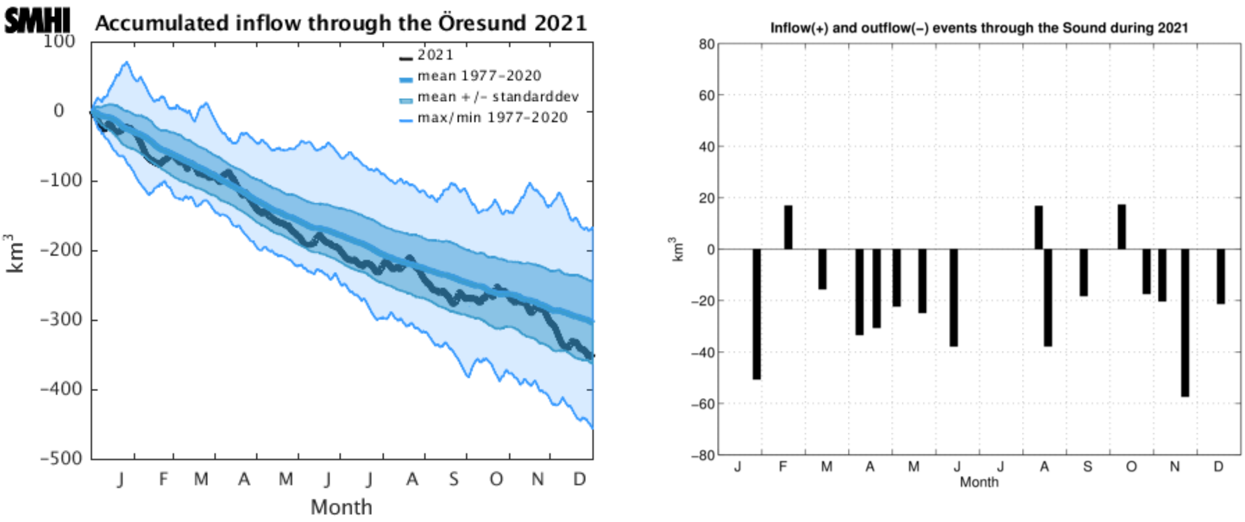

Figure 5. Left: Accumulated inflow (volume transport) through the Sound (Öresund) during 2021 in comparison to mean inflow/outflow 1977-2020. Right: Inflow (+) and outflow (-) events during 2021 that was longer than 5 days and with volume larger than 15 km^3. [Revised summary of inflow events, SMHI, 2022].

4.2 Preliminary results for 2022

The frequency of inflows to the Baltic Sea have been similar during recent years. The latest major inflow to the Baltic Sea occurred in late 2014. After that a series of inflows occurred during the period 2014-2016, but during 2017-2018 only minor inflows was observed. In late 2019, one somewhat larger inflow was noted. During 2020-2022 the frequency of small inflows ranged from 3-4 per year. In 2022, four inflow events were observed through the Sound all around 20 km^3. See figure 6.

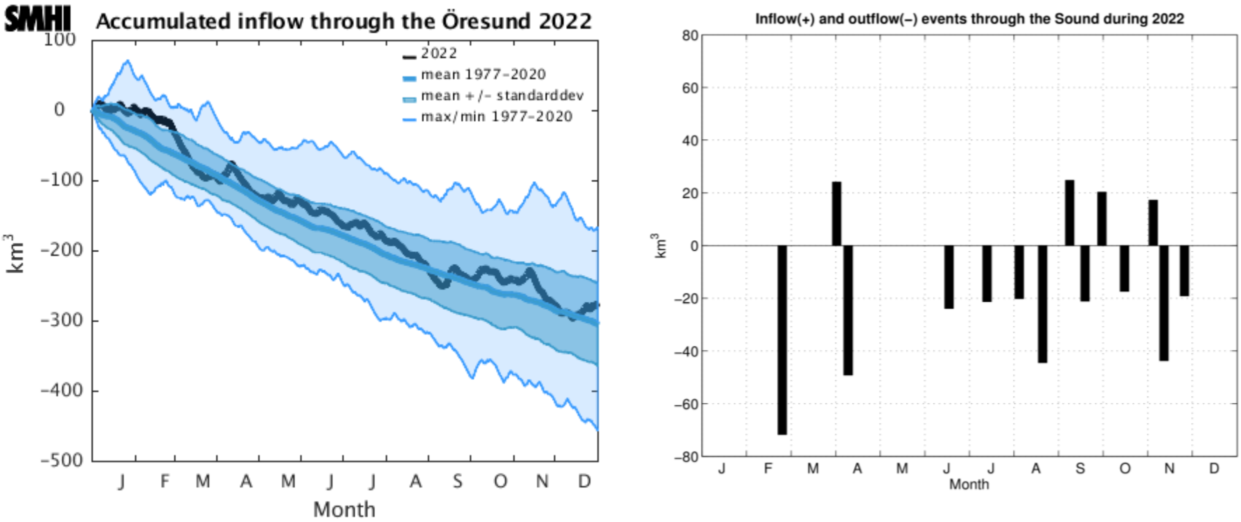

Figure 6. Left: Accumulated inflow (volume transport) through the Sound (Öresund) during 2022 in comparison to mean inflow/outflow 1977-2020. Right: Inflow (+) and outflow (-) events during 2022 that was longer than 5 days and larger than 15 km^3. [Revised summary of inflow events, SMHI, 2023].

In the Arkona Basin the oxygen situation in the deep water normally follows the annual cycle with well oxygenated conditions during winter and spring, followed by decreased oxygen concentrations during summer and recovery during late autumn. In 2022 the effects of the three inflows during autumn were clearly seen as large variations in the bottom water oxygen. Acute hypoxic conditions, dissolved oxygen concentration below 2 ml/l was found in July and August. In September and October, the oxygen conditions were well above 4 ml/l followed by acute hypoxic conditions in November. In December the levels of oxygen increased again to well above 4 ml/l. The rapid change in oxygen concentrations are probably due to inflowing water with different origin and conditions. The low oxygen conditions that was noted in November could be inflowing water with low oxygen concentrations, from the deeper parts of the Belt or Kattegat, that is flushed into the Baltic Proper as new inflowing water enters [SMHI, 2022].

The oxygen situation, below the halocline at Hanö Bight, were hypoxic throughout the year. The bottom water was near-anoxic, with oxygen concentrations close to 0 ml/l. From May to August hydrogen sulphide was measured in the bottom water but effects of the autumn inflows were seen here as the bottom water oxygen increased above 2 ml/l in October. But the effects did not last for long, as the oxygen dropped again to 0 ml/l during the coming months. In the Bornholm Basin the oxygen conditions throughout the year were similar to those in Hanö Bight. However, the effects of the inflows came later. The temperature of the inflowing water was higher than normal, around 10°C while the salinity was normal.

Further into the south east Baltic Proper at station BCSIII-10 the oxygen conditions in the deep water also changed between anoxic and hypoxic conditions over the year, probably due to pulses of oxygenated water passing through.

In the deep water at Gotland Deep (BY15), in the Eastern Gotland Basin, concentrations of hydrogen sulphide increased during the year. From depths exceeding 225 meters depth the concentrations of hydrogen sulphide varied between 110 - 190 µmol/l over the year. The concentrations in the deep water are now at record high levels, never recorded before. See Figure 7, Appendix 1 and SMHI cruise reports from 2022 [SMHI, 2023]. The oxygen situation further up in the water column just below the permanent halocline remained stable over the year. Acute hypoxic conditions, below 2 ml/l, was found at approximately 70 meters depth. From 80-125 meters depth near anoxic conditions prevailed with oxygen concentrations near zero or low concentrations of hydrogen sulphide.

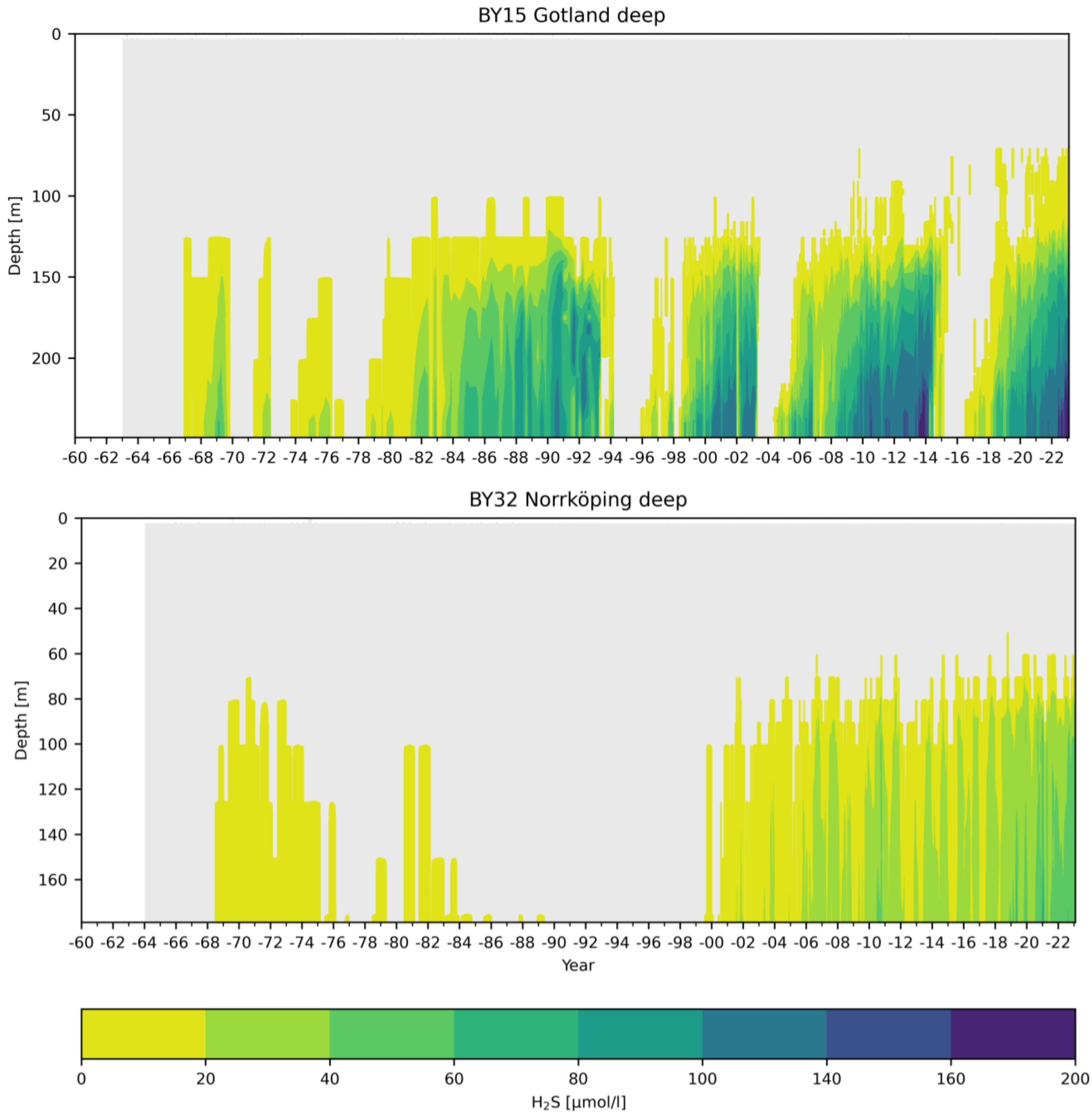

Figure 7. Concentration of hydrogen sulphide (H_2S) at Gotland Deep (BY15) in Eastern Gotland Basin (top) and Norrköping Deep (BY32) in the Wester Gotland Basin from 1960-2022. Grey color signifies no hydrogen sulphide present and white indicate that data is missing.

The oxygen situation in the deep water in the Northern Gotland Basin shows similar development as in the Eastern Gotland Basin. The concentration of hydrogen sulphide in the bottom water also show values elevated above what is normal throughout the year.

Also, in the Western Gotland Basin the severe stagnation continues. The concentrations of hydrogen sulphide is higher than normal and are at a record high level, never measured before, see appendix 1. In the northern parts, at station Norrköping Deep (BY32), acute hypoxia was found from 65-75 meters depth and anoxic conditions from 80-90 meters while in the southern parts, at station Karlsö Deep (BY38) low oxygen was found shallower. Hypoxia from 50-70 meters depth and anoxia from 60-80 meters. [SMHI, 2022]

The updated results for 2021 and the preliminary results for 2022 show that the severe oxygen conditions in the Baltic Proper after the regime shift in 1999 continues. Levels of anoxia increased somewhat compared to the results for 2020, while the extent of hypoxia remained largely unchanged. The increase in anoxia was seen in the southern Baltic Proper and in the Gulf of Finland.

The small improvements seen during 2020 in the southern parts of the Baltic Proper did not last for long and already in 2021 the conditions deteriorated. In late 2022 a series of inflows could possibly improve the oxygen situation. However, the inflowing water was warmer than normal and not saline enough to reach the deeper part of the central basins.

Note that the 2022 results are preliminary and that there are uncertain results in the south eastern Baltic Proper that affects the overall results; however, the results are based on extensive data sets with essential data contributions from almost all countries around the Baltic Proper. See all data contributors in the Acknowledgement below.

5 Conclusions

- In 2021 anoxia was found at 1/5 (21%) of the bottom areas and 1/3 (31%) suffered from hypoxia during the autumn period.
- Preliminary results for 2022 shows similar results as 2021. About 1/5 (21%) of the bottom areas suffer from anoxia and approximate 1/3 (34%) suffered from hypoxia during the autumn 2022.
- The severe oxygen conditions in the Baltic Proper continues. The areal extent and volume of anoxia are still elevated and follow the development that have prevailed since the regime shift in 1999.
- The concentration of hydrogen sulphide is above normal in all the basins around Gotland. In the Eastern and Western Gotland Basin hydrogen sulphide in the bottom water has reached extremely high levels, never recorded before.
- The inflows that occurred during 2021 - 2022 did only affect the oxygen situation in southern parts of the Baltic Proper. No inflows reached the deeper basins around Gotland.

6 Acknowledgement

Many thanks to Tycjan Wodzinowski, National Marine Fisheries Research Institute in Poland, for sending data from two surveys part of the project “Polish Multiannual Fisheries Data Collection Programme”.

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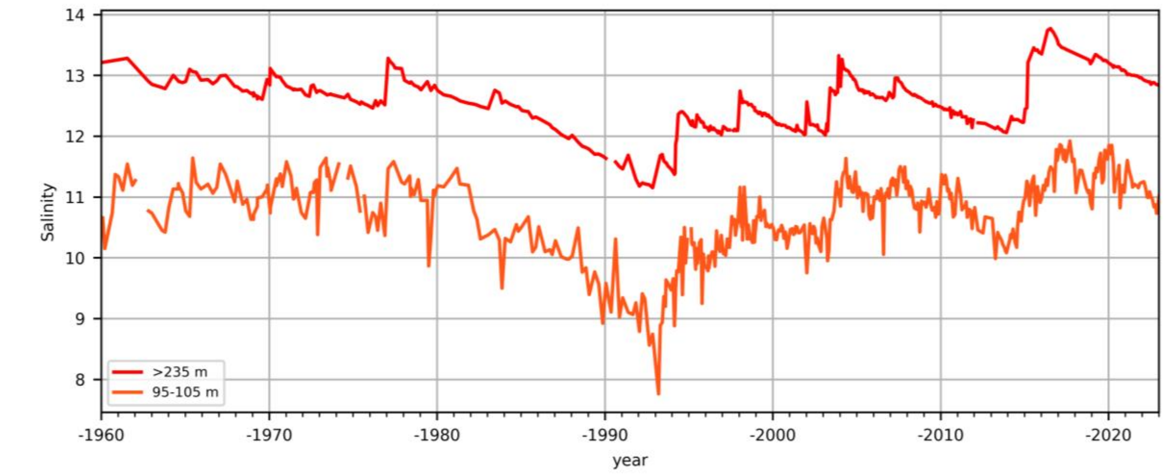
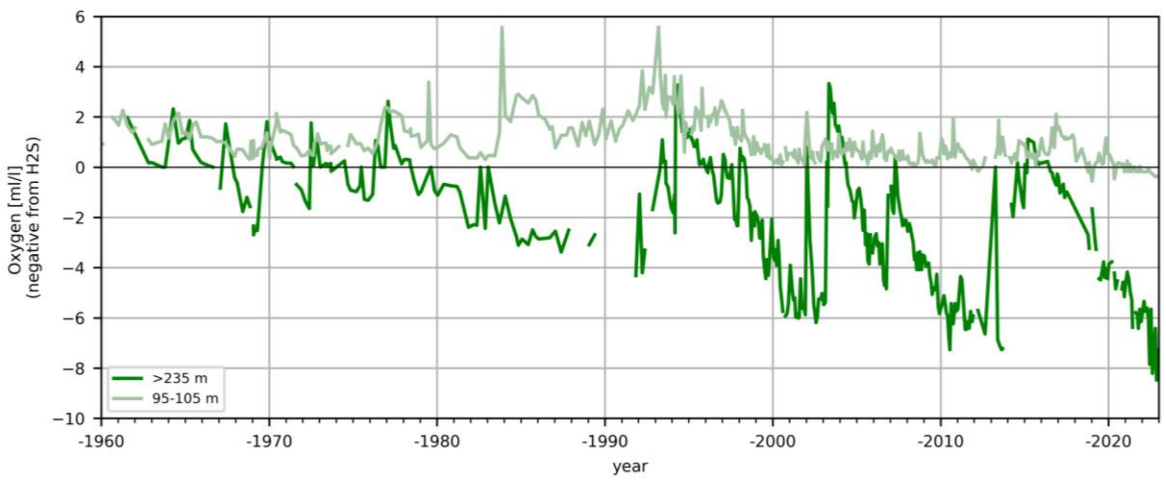
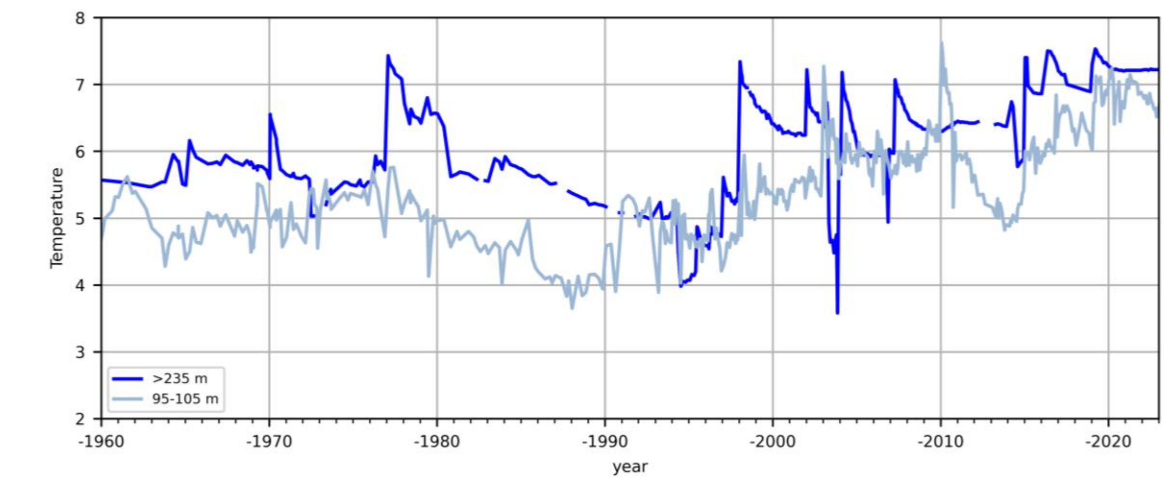
Appendix 1

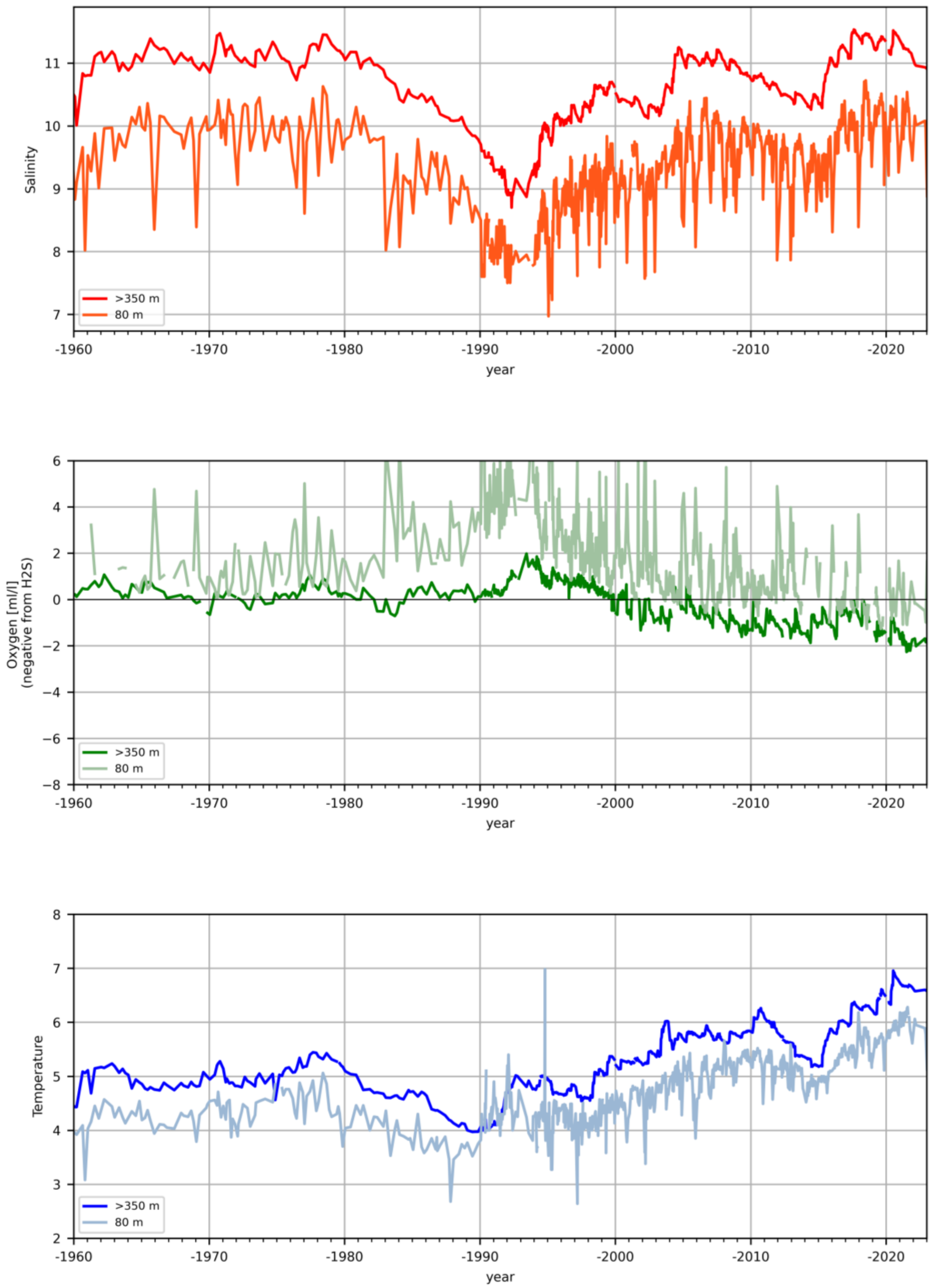
Temperature, salinity and oxygen in the Eastern Gotland Basin at station BY15, 1960-2022





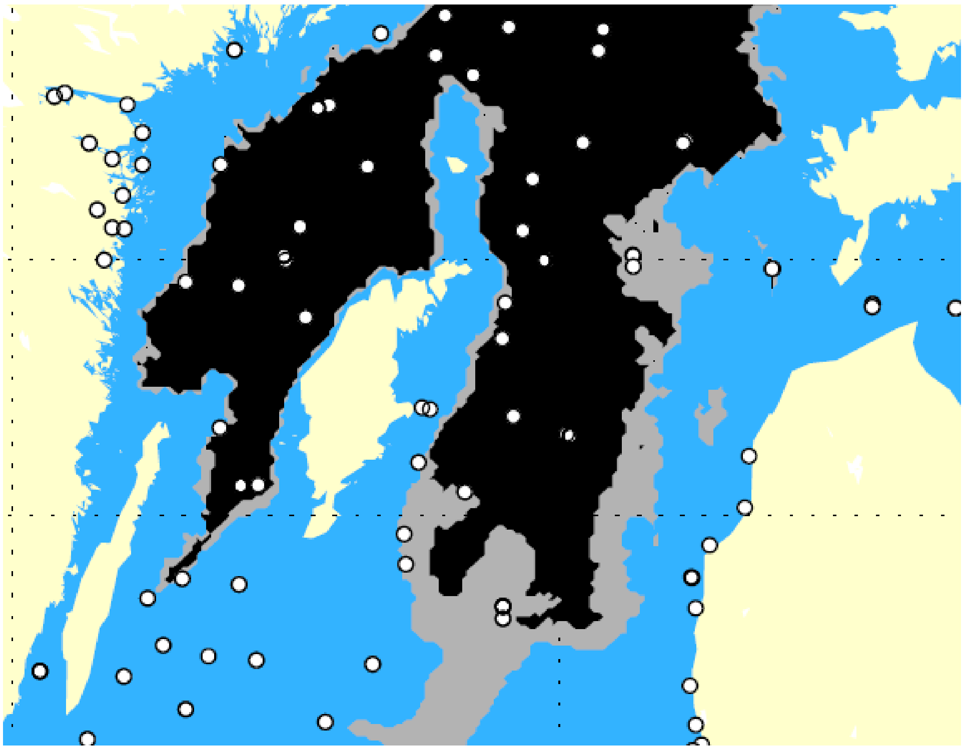


Temperature, salinity and oxygen in the Western Gotland Basin at station BY31, 1960-2022

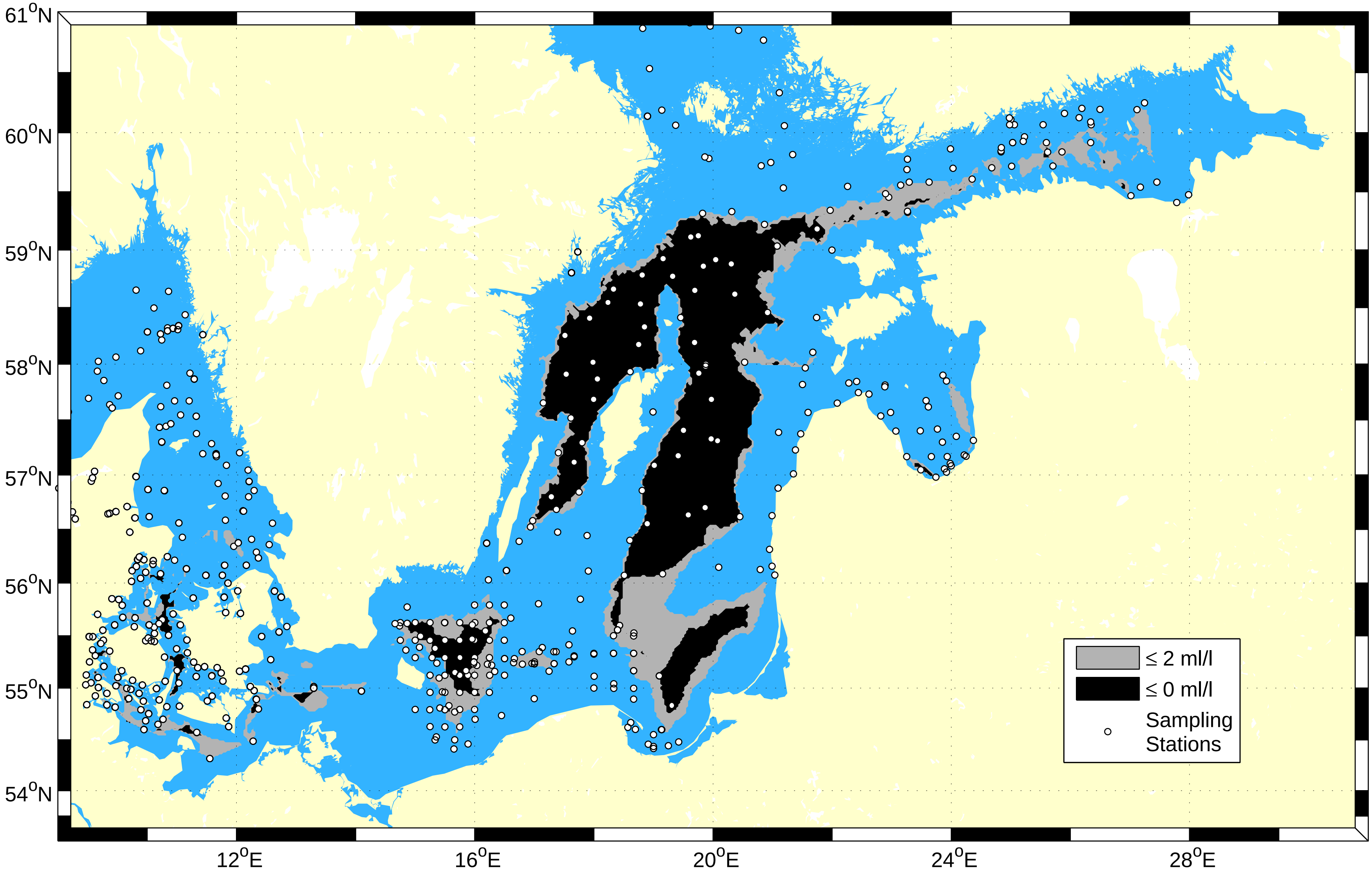


Appendix 2 - Anoxic and hypoxic areas in the Baltic Sea

- updated maps 1960-2022

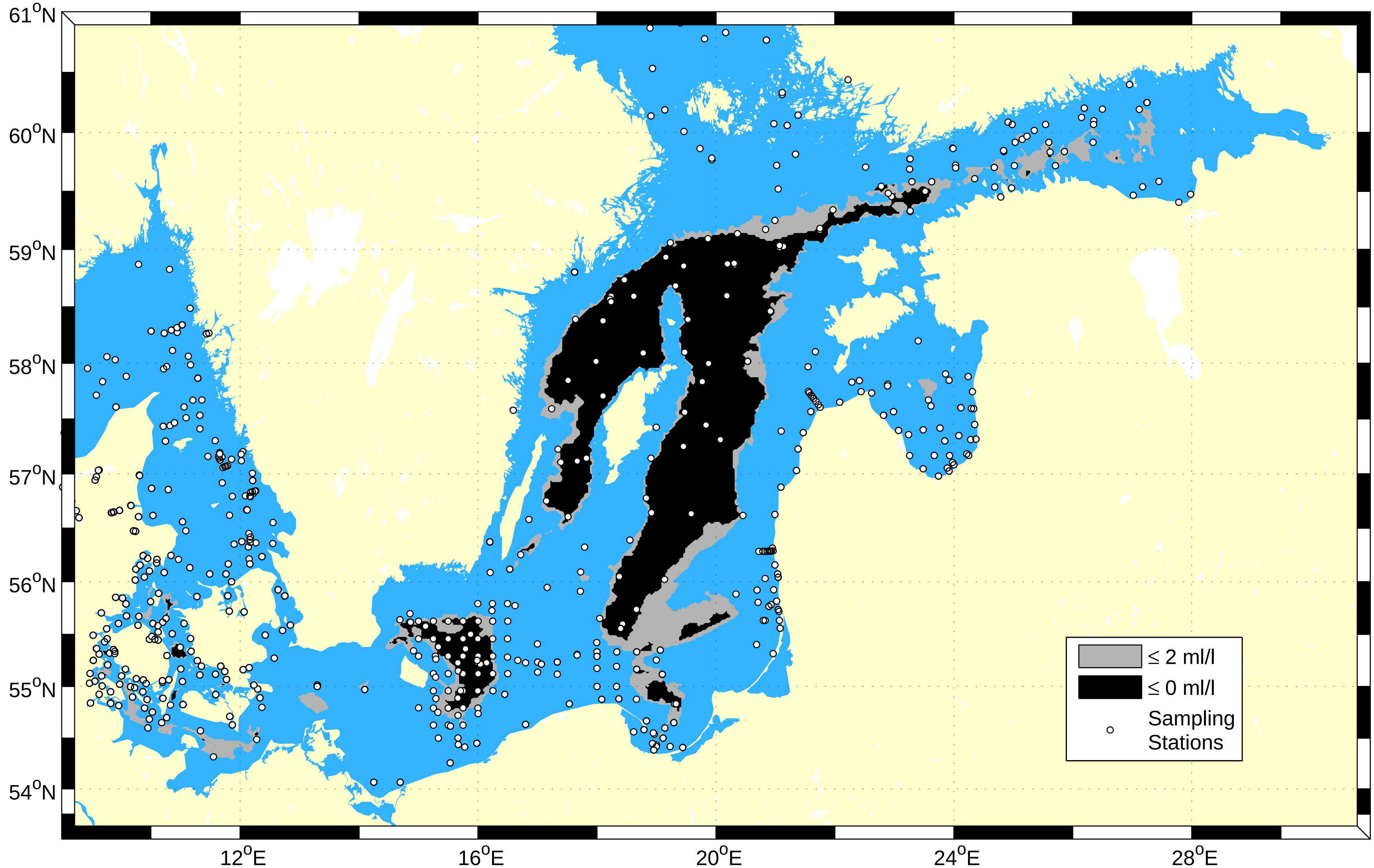


Extent of hypoxic & anoxic bottom water, Autumn 2022



Created:
February 2023

Extent of hypoxic & anoxic bottom water, Autumn 2021



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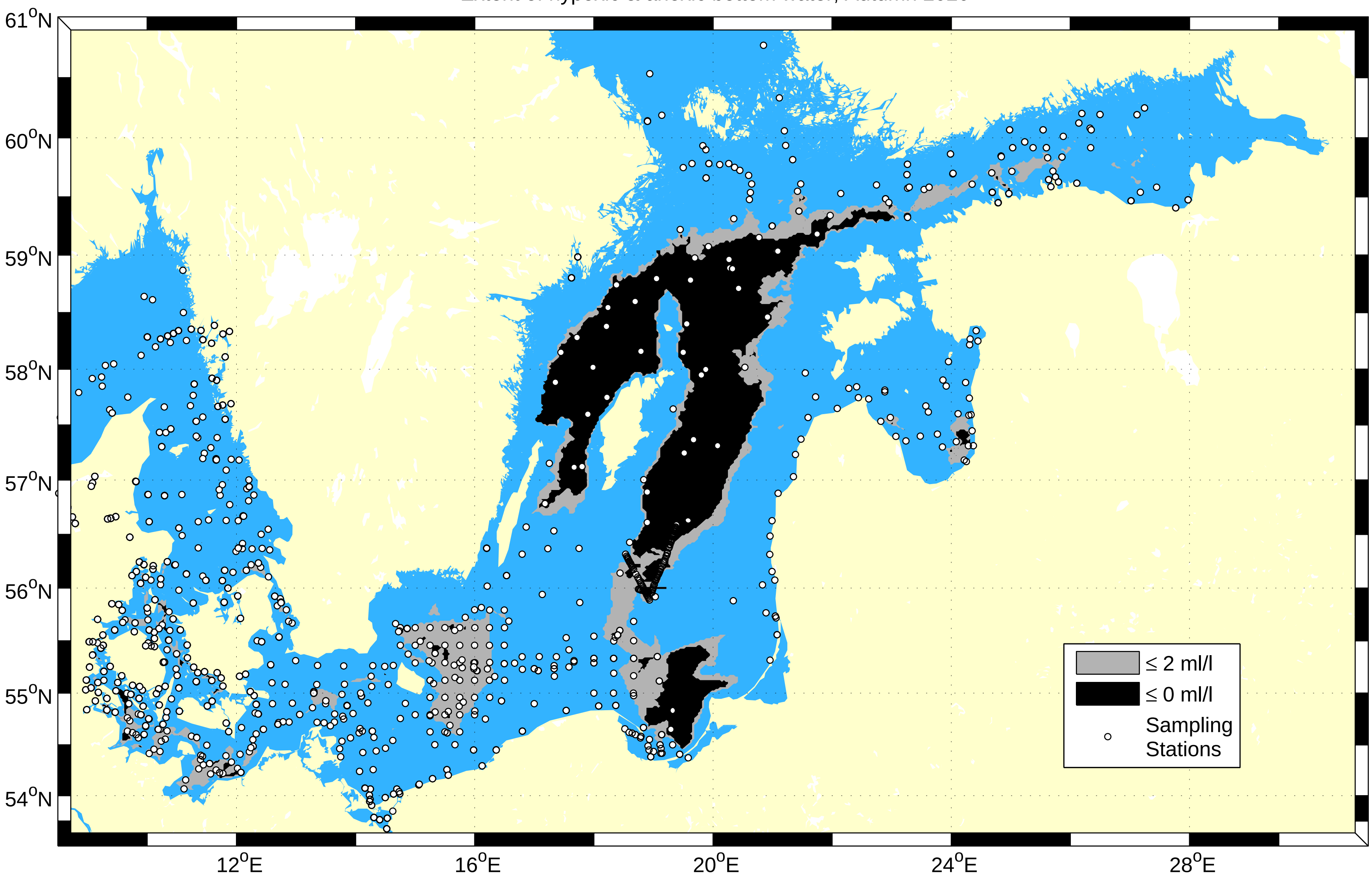
Extent of hypoxic & anoxic bottom water, Autumn 2020



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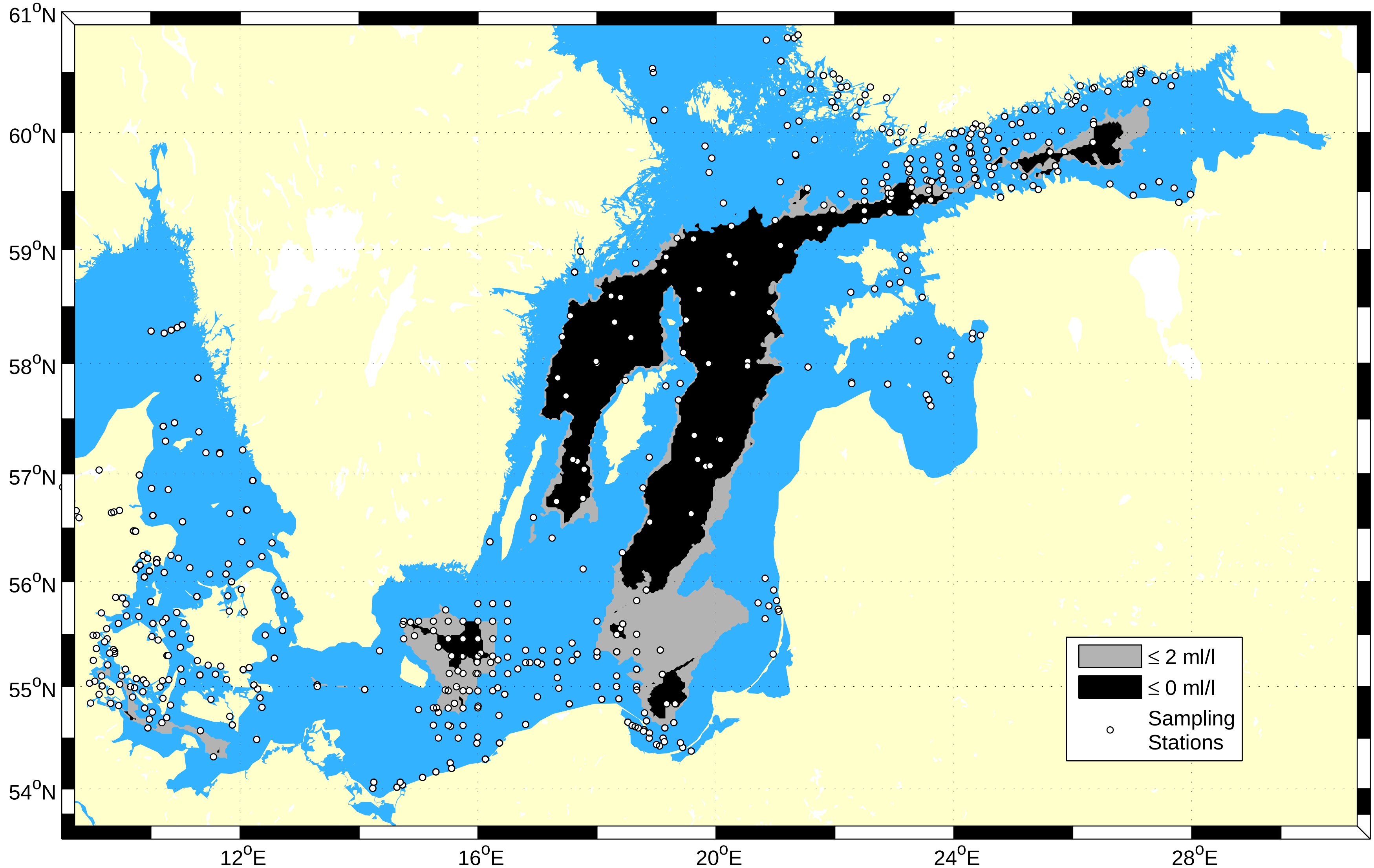
Extent of hypoxic & anoxic bottom water, Autumn 2019



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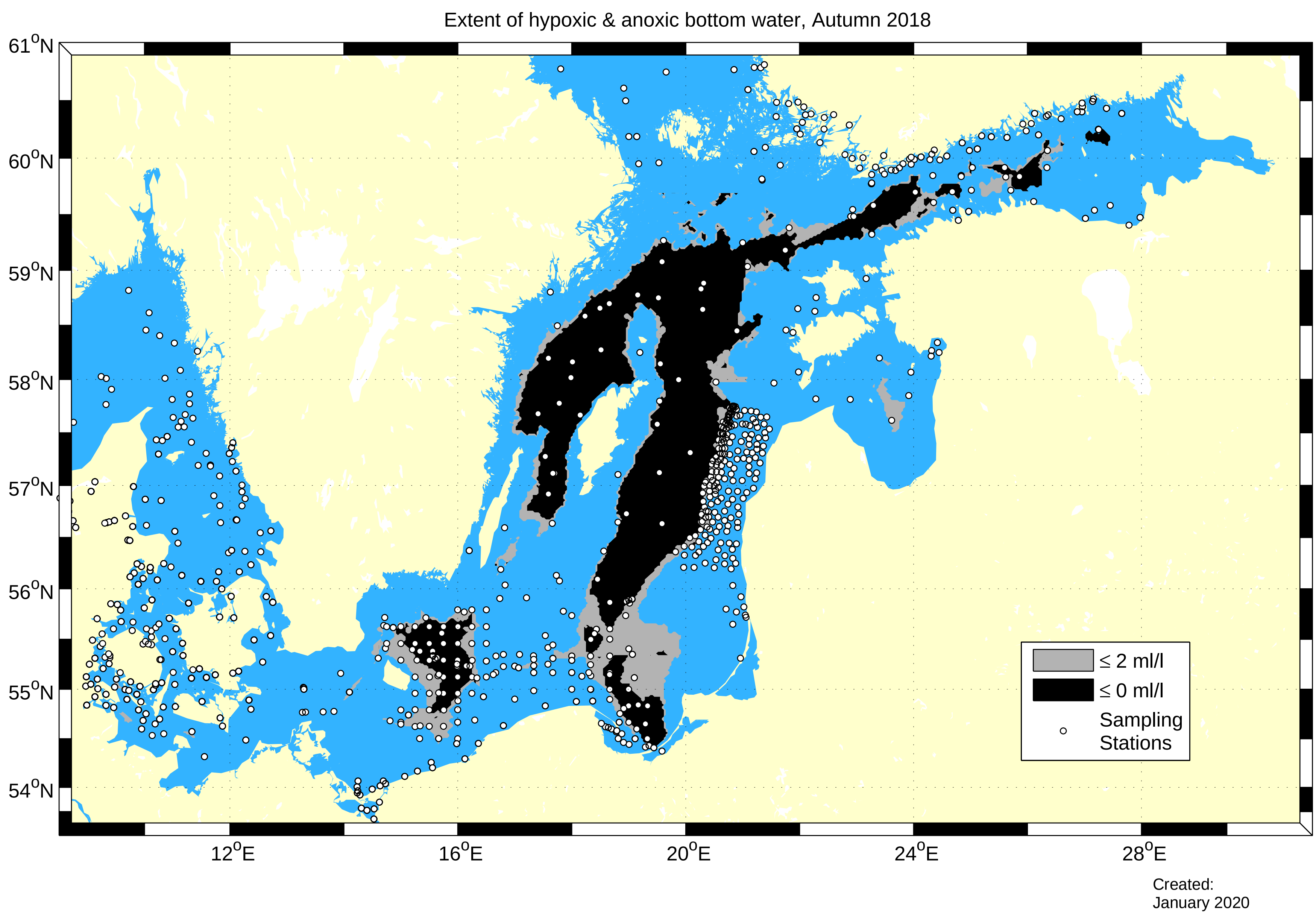
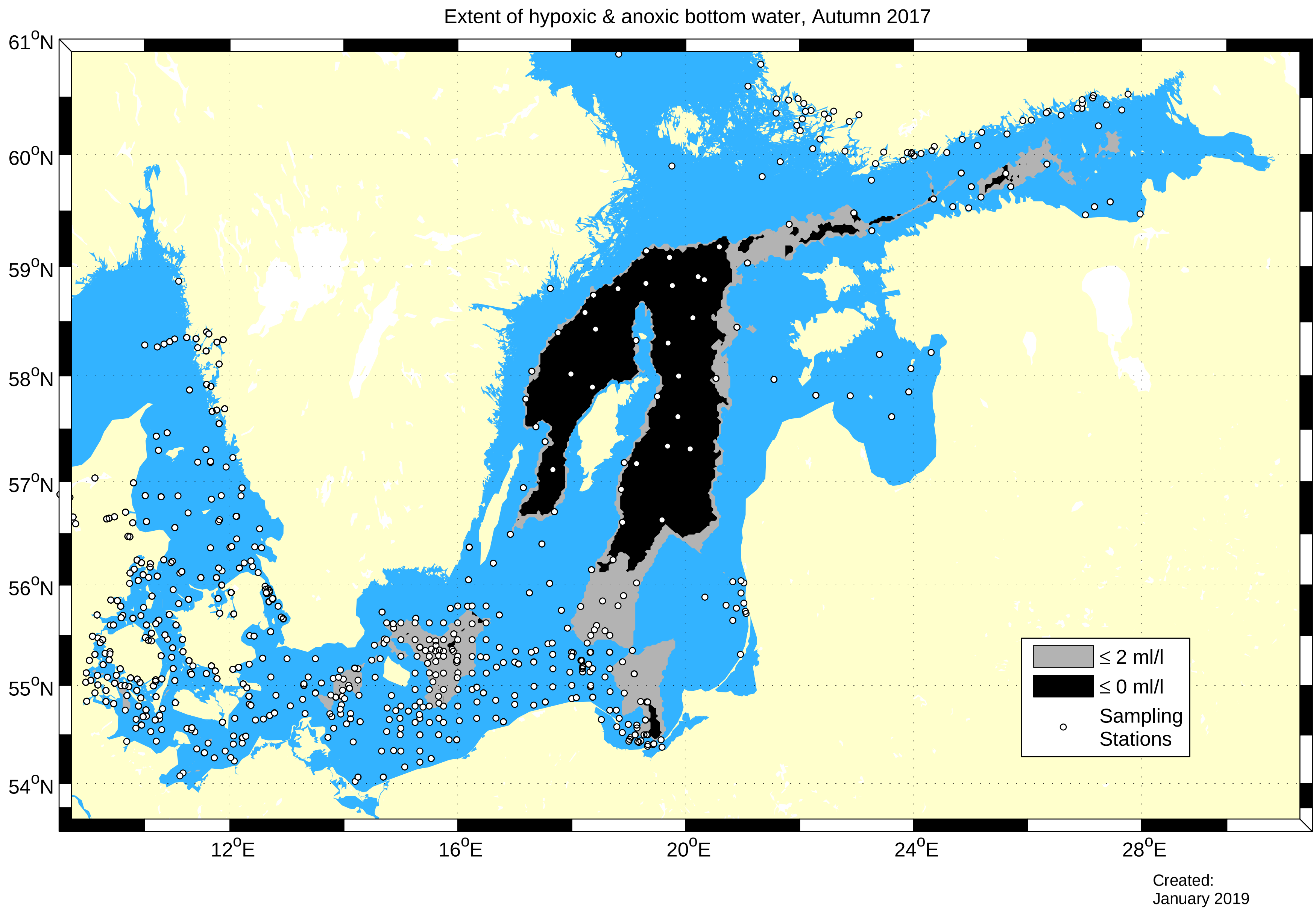
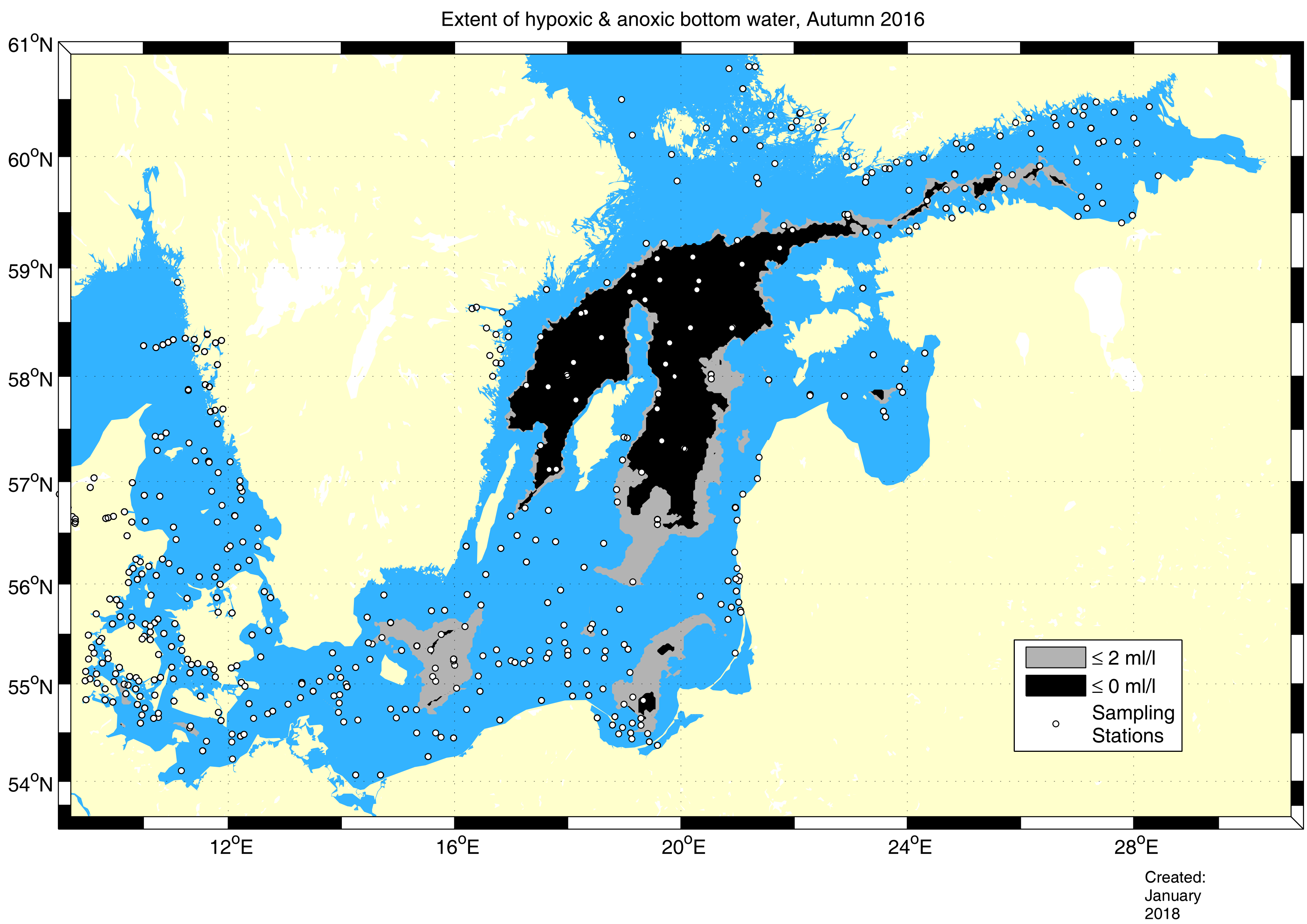
February 2021



Extent of hypoxic & anoxic bottom water, Autumn 2018
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
Created: January 2020


Extent of hypoxic & anoxic bottom water, Autumn 2017
61^{o}N
60^{o}N
59^{o}N
58^{o}N
57^{o}N
56^{o}N
55^{o}N
54^{o}N
12^{o}E
16^{o}E
20^{o}E
24^{o}E
28^{o}E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
Created: January 2019


Extent of hypoxic & anoxic bottom water, Autumn 2016
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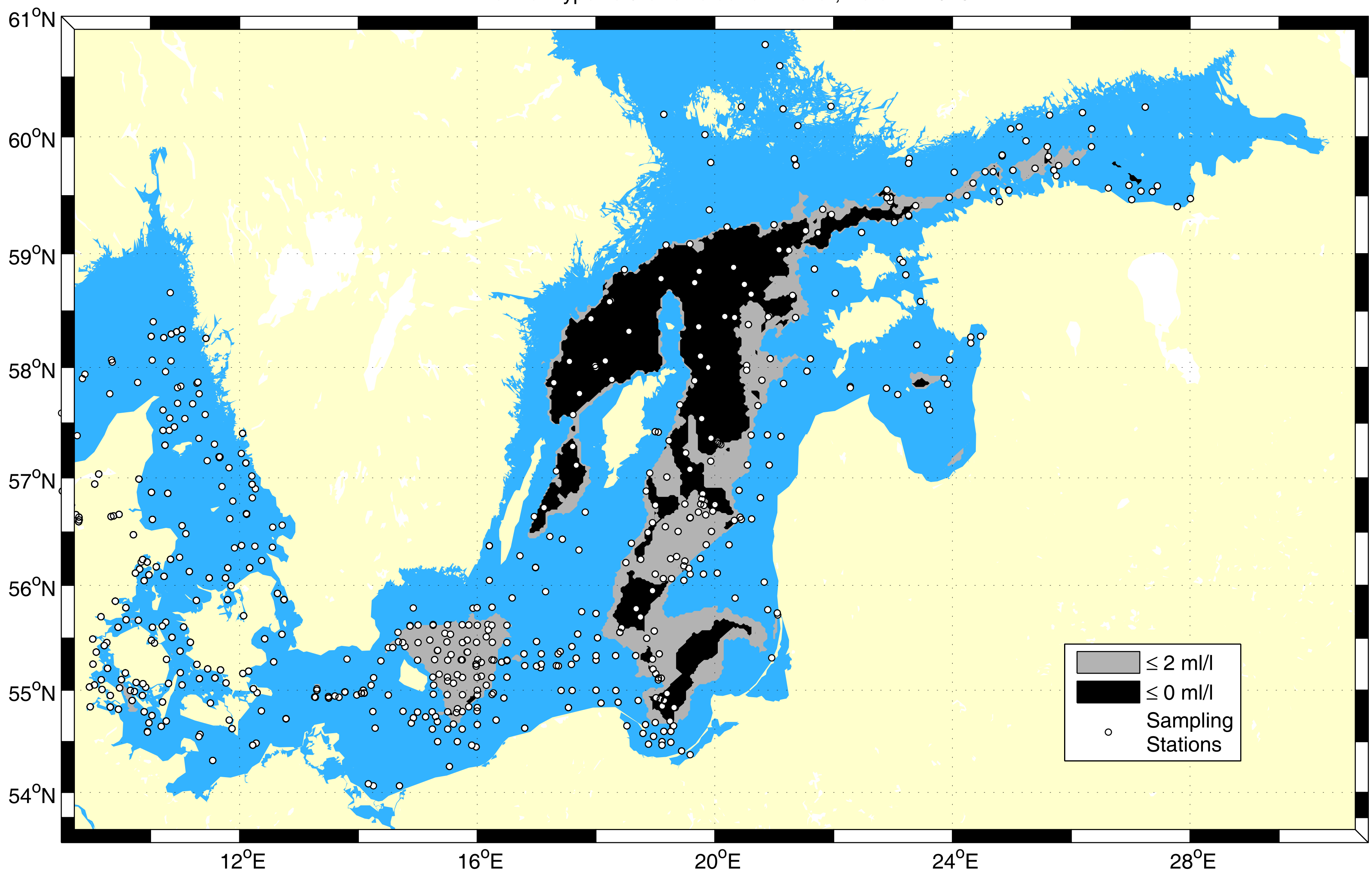
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
Created: January 2018

Extent of hypoxic & anoxic bottom water, Autumn 2015



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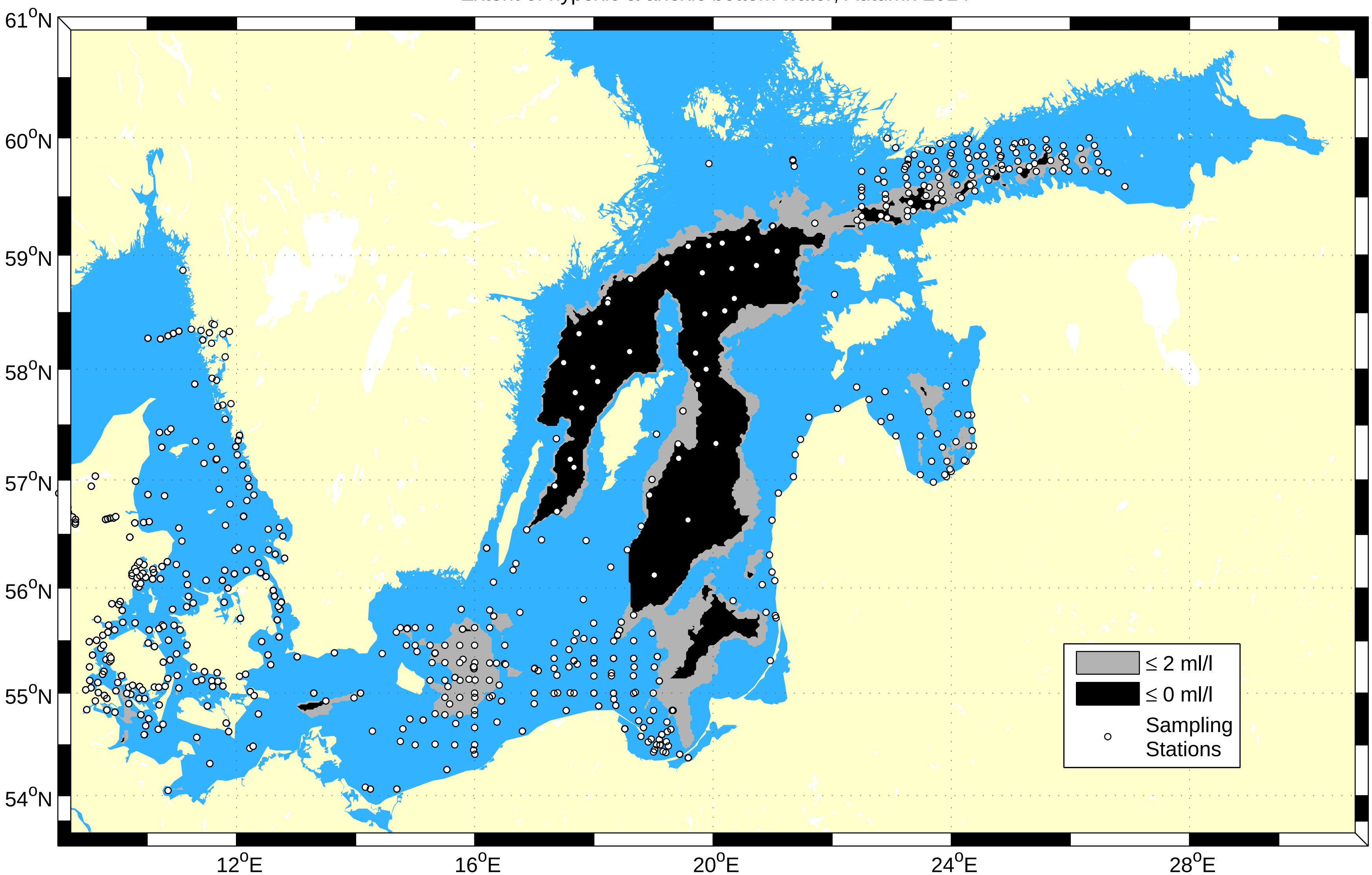
Extent of hypoxic & anoxic bottom water, Autumn 2014



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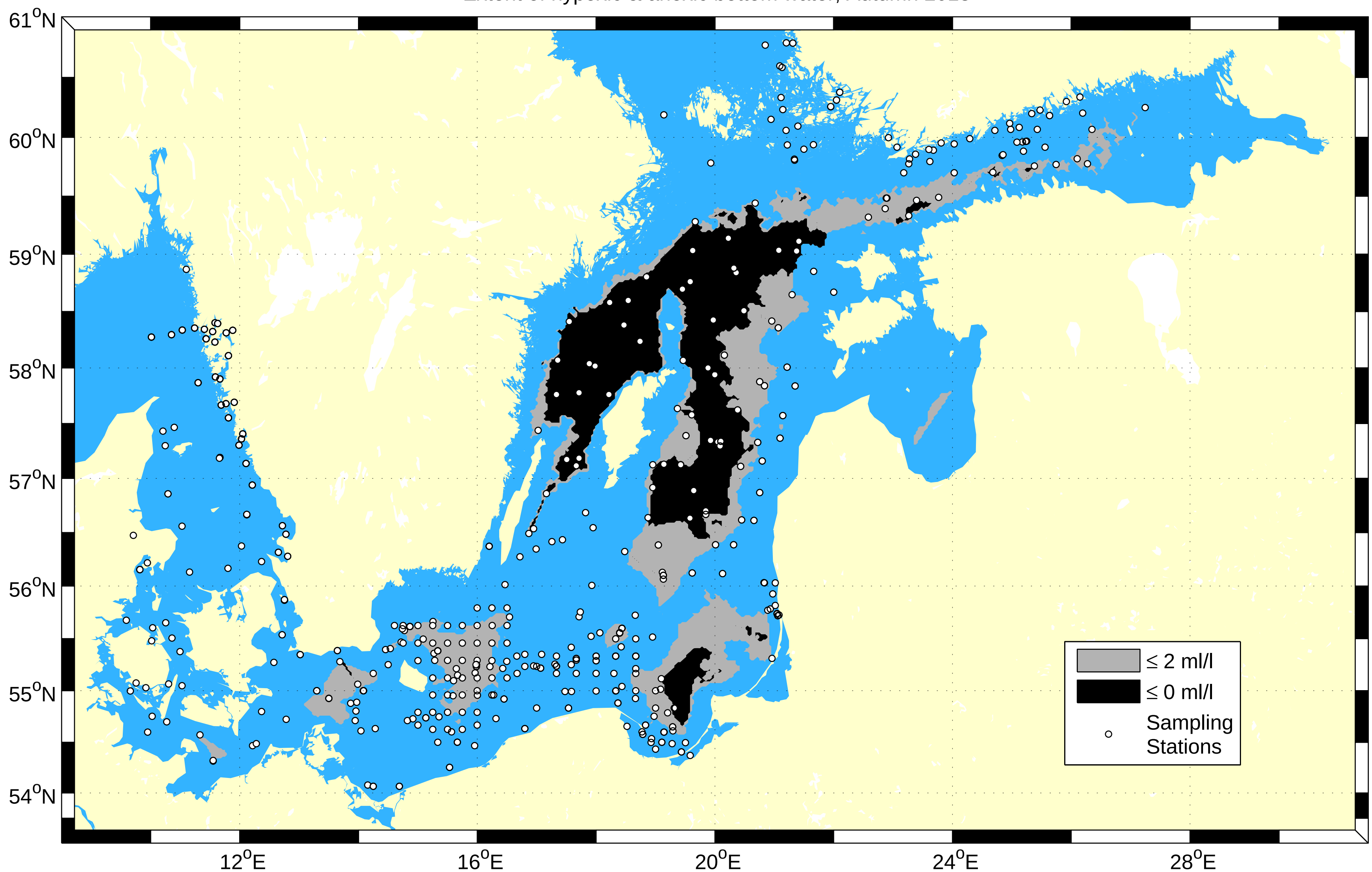
November
2015

Extent of hypoxic & anoxic bottom water, Autumn 2013



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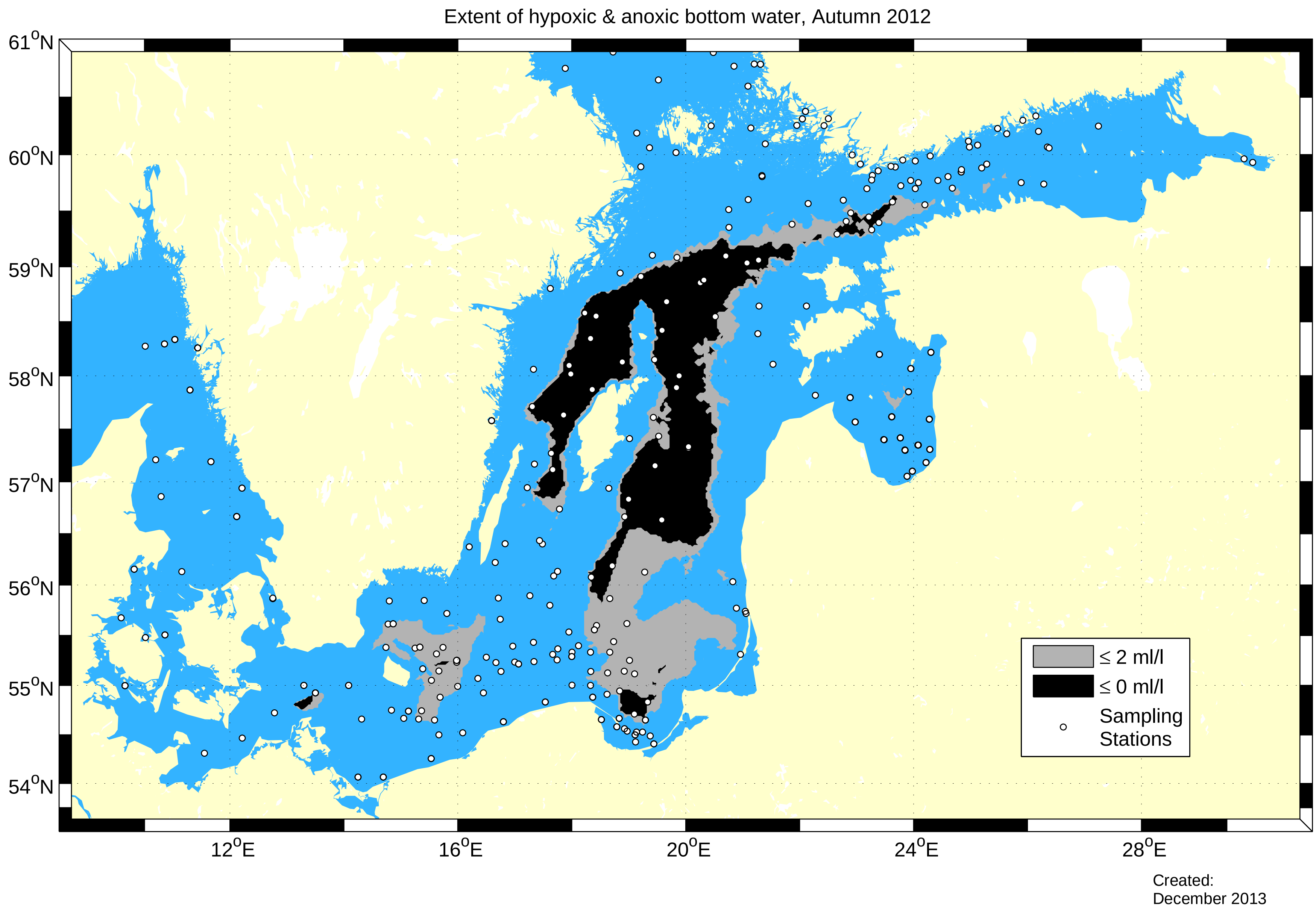
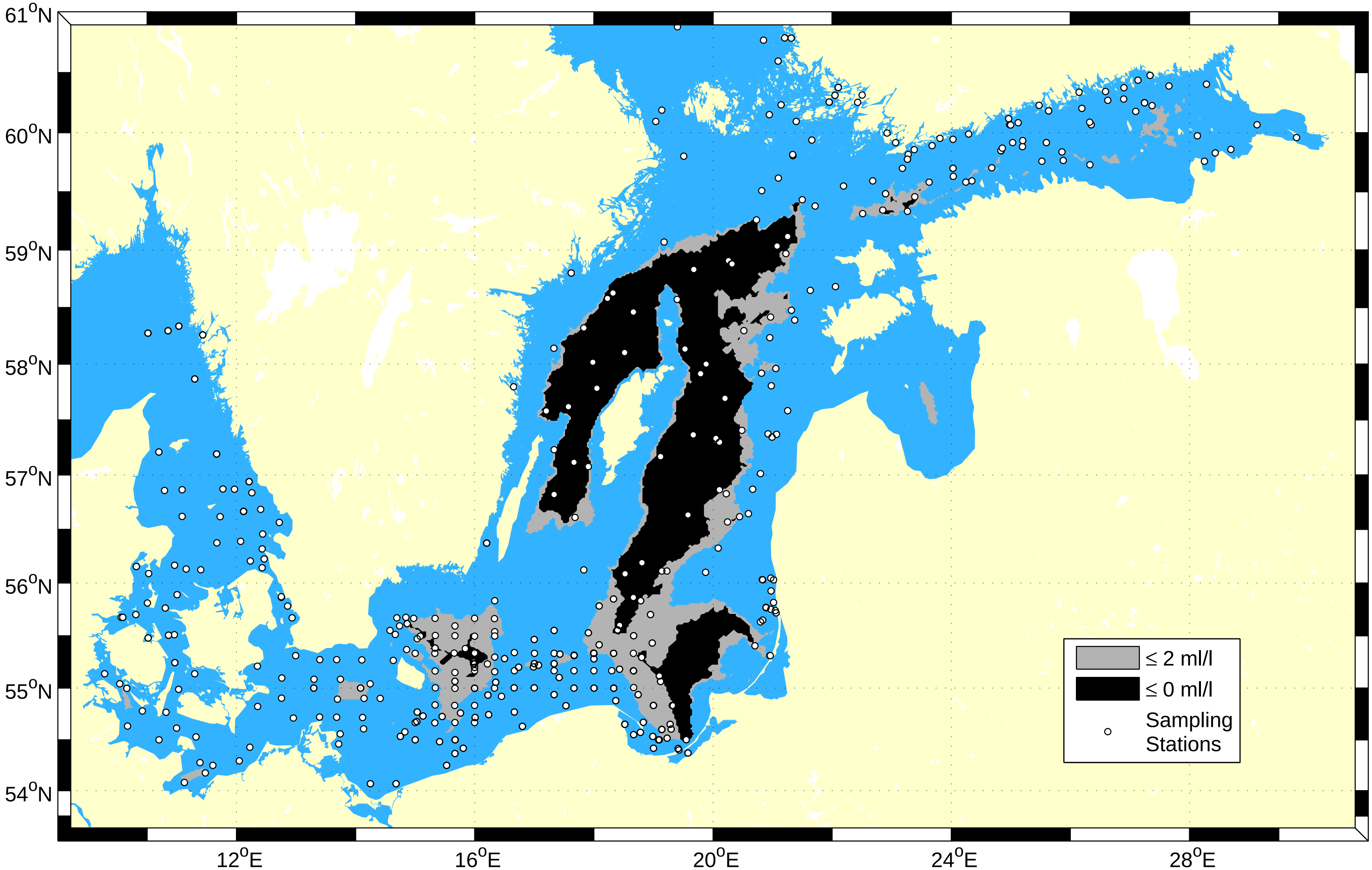
December 2014


Extent of hypoxic & anoxic bottom water, Autumn 2012
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations
Created:
December 2013

Extent of hypoxic & anoxic bottom water, Autumn 2011



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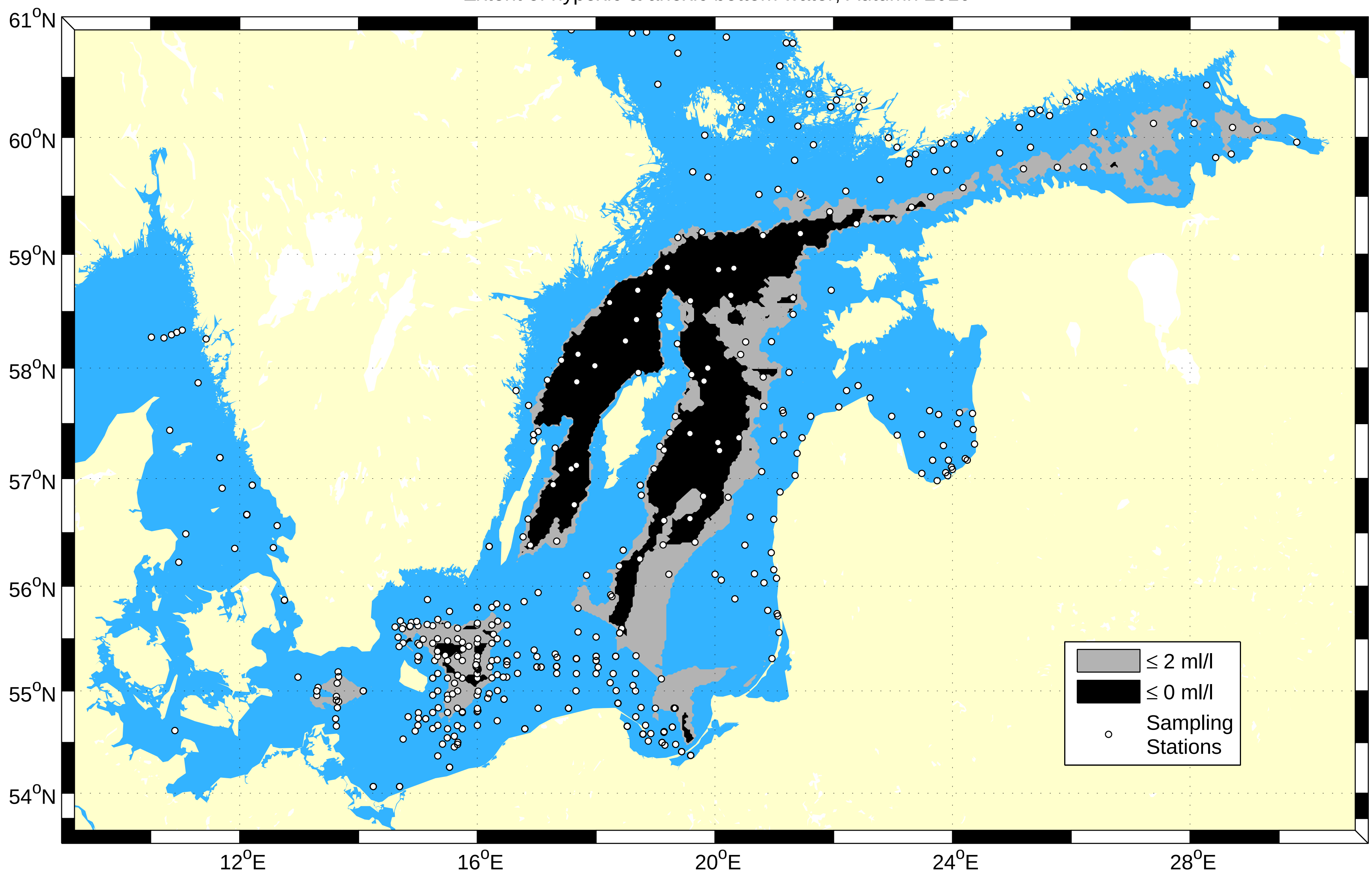
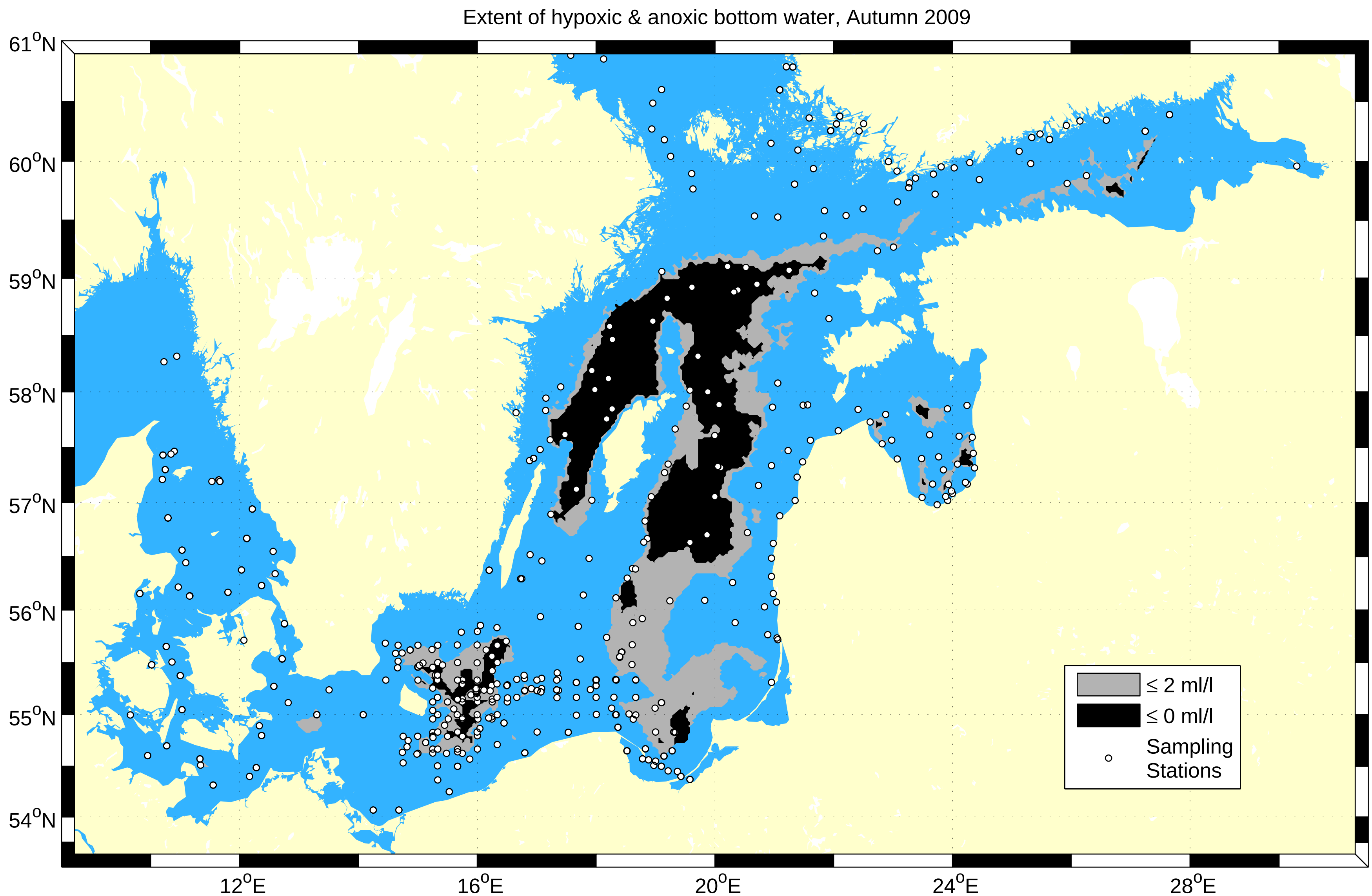
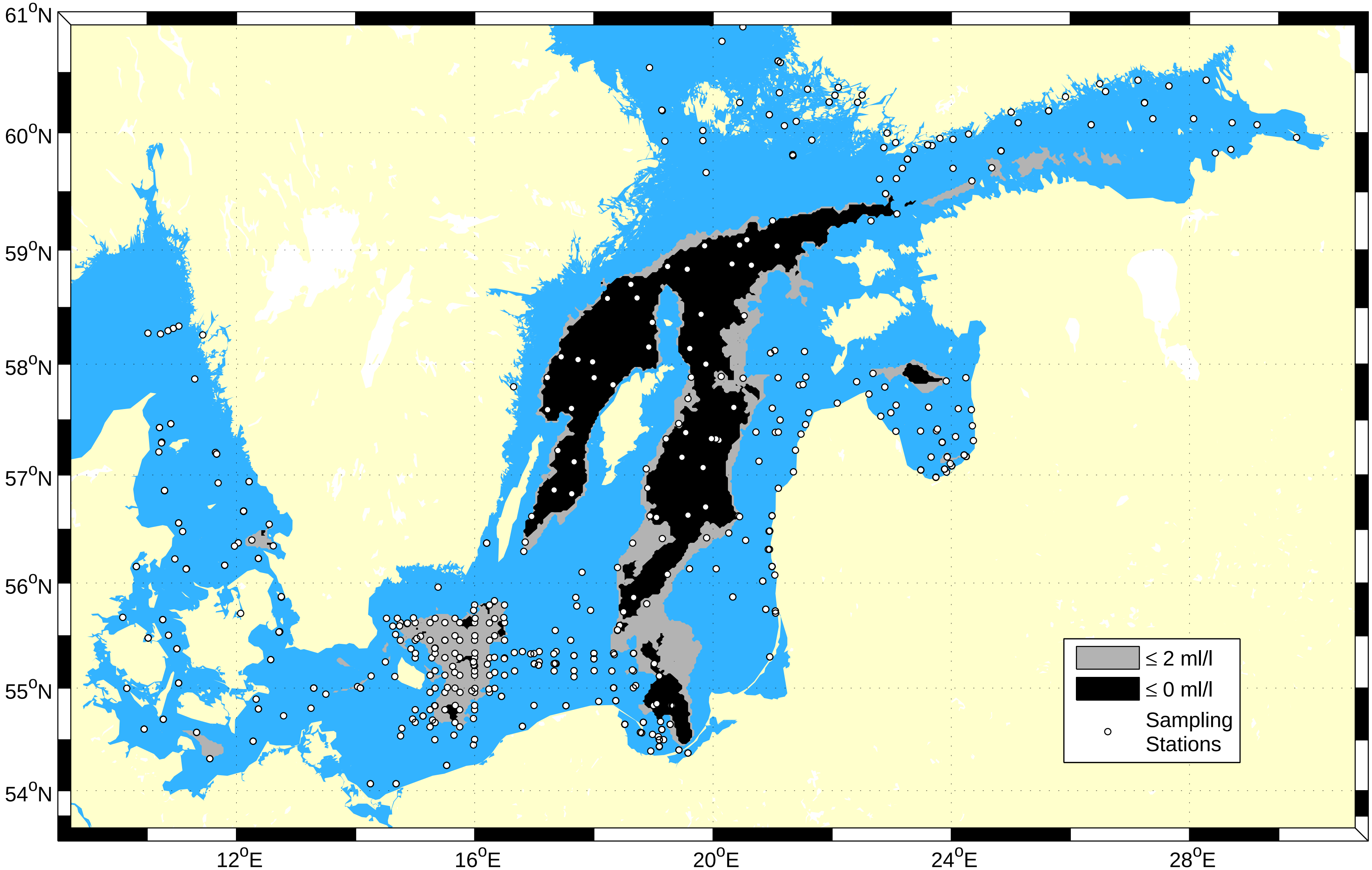
Extent of hypoxic & anoxic bottom water, Autumn 2010



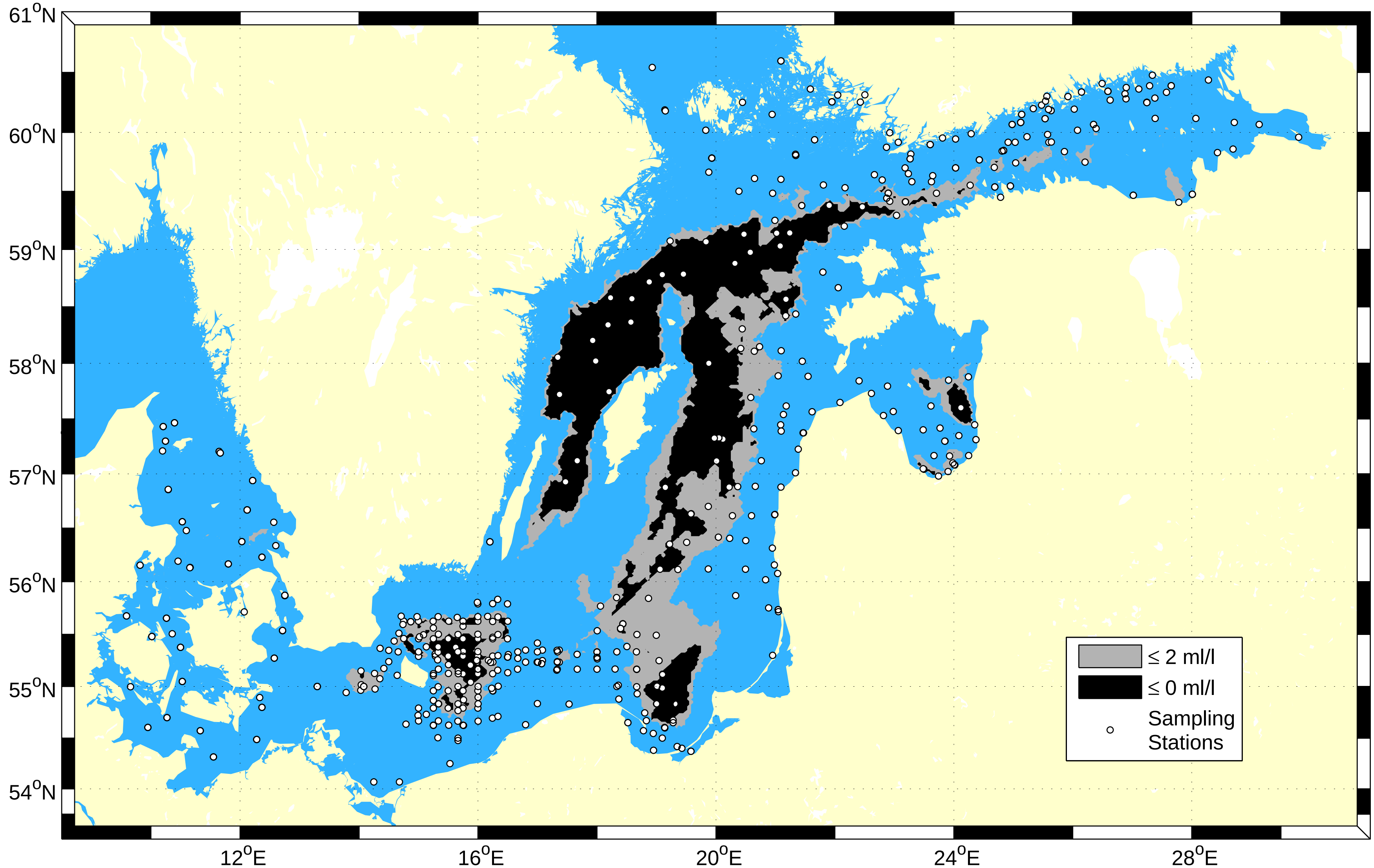


Extent of hypoxic & anoxic bottom water, Autumn 2009
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

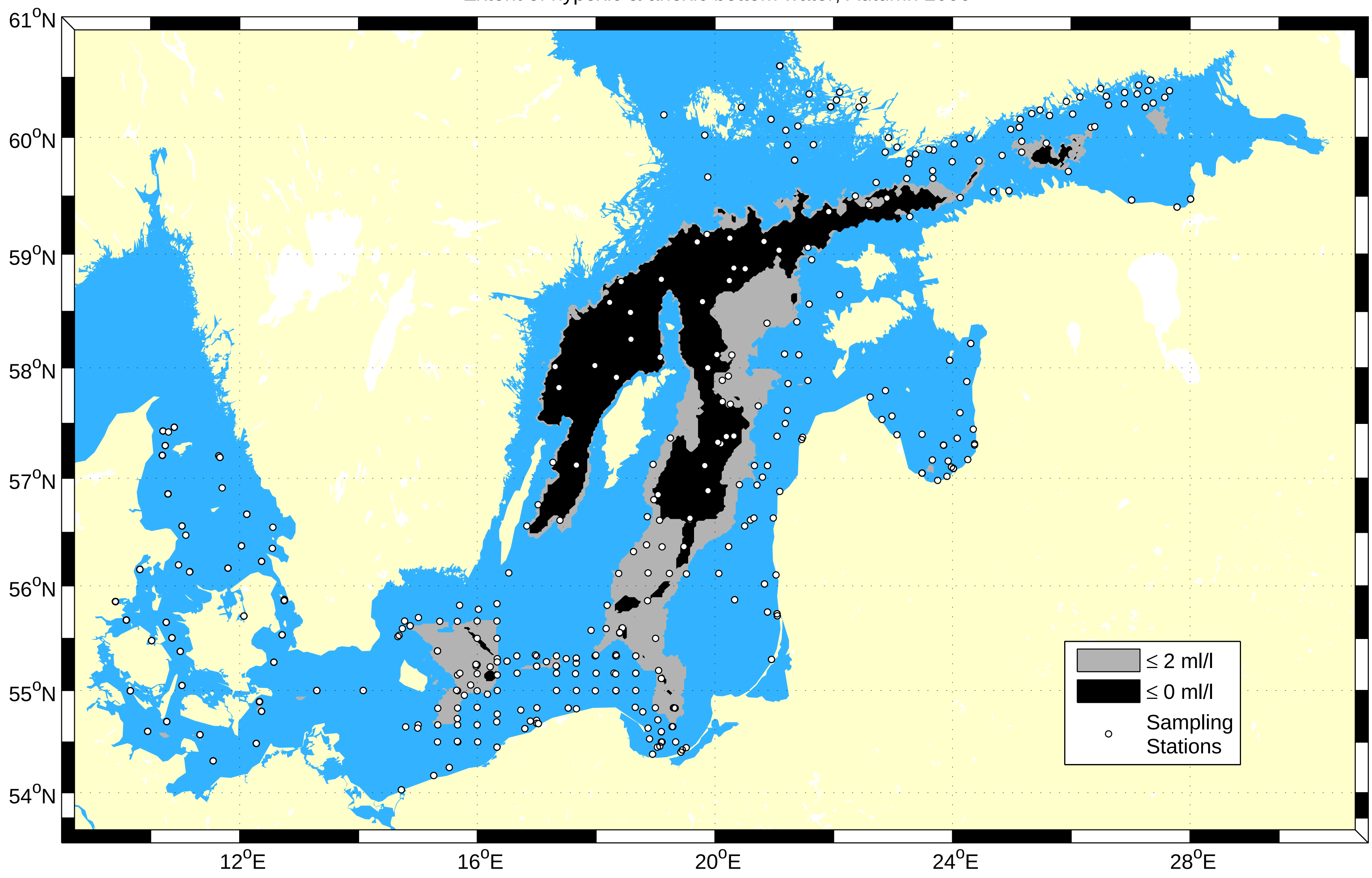
Extent of hypoxic & anoxic bottom water, Autumn 2008

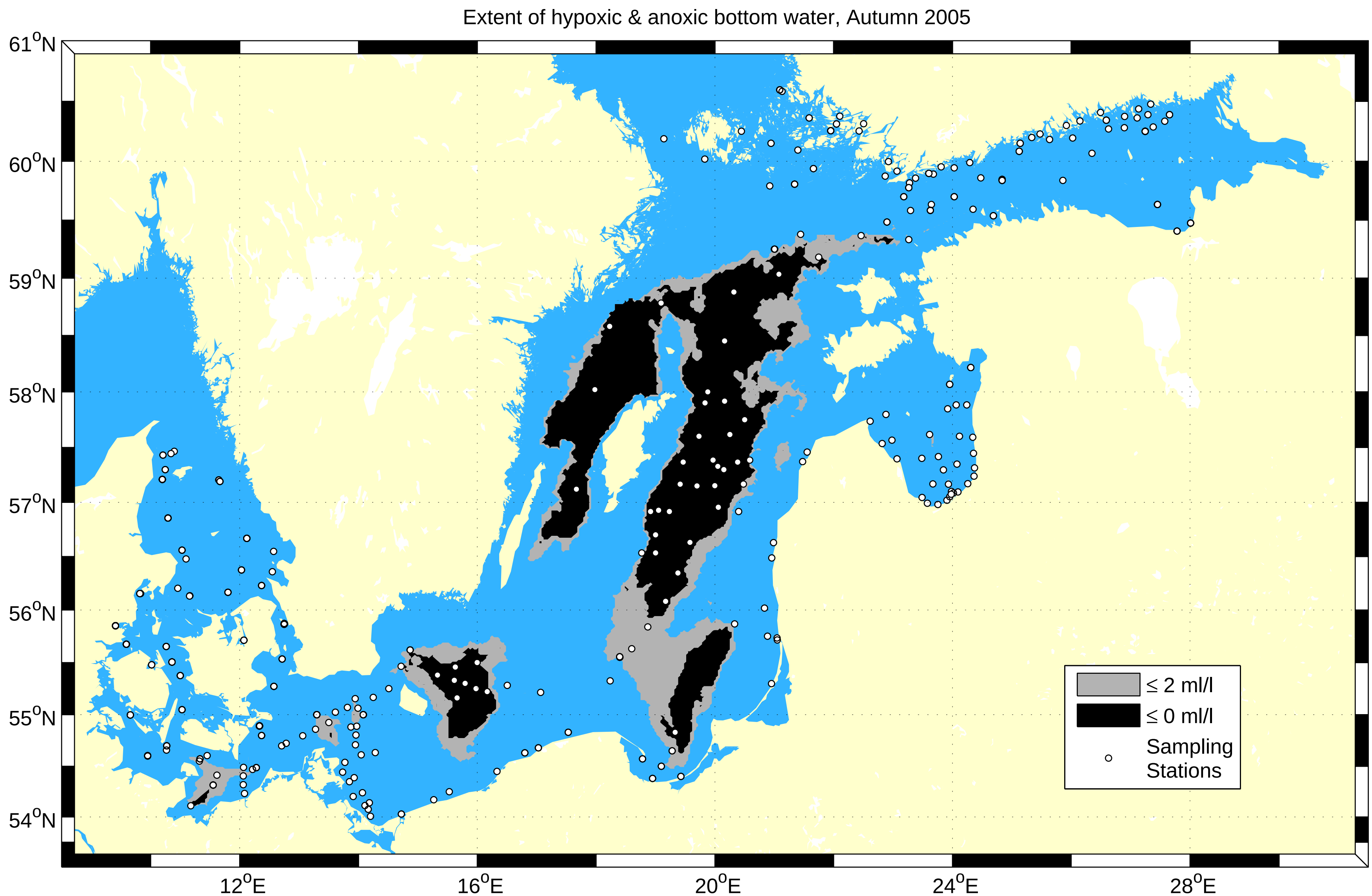


Extent of hypoxic & anoxic bottom water, Autumn 2007

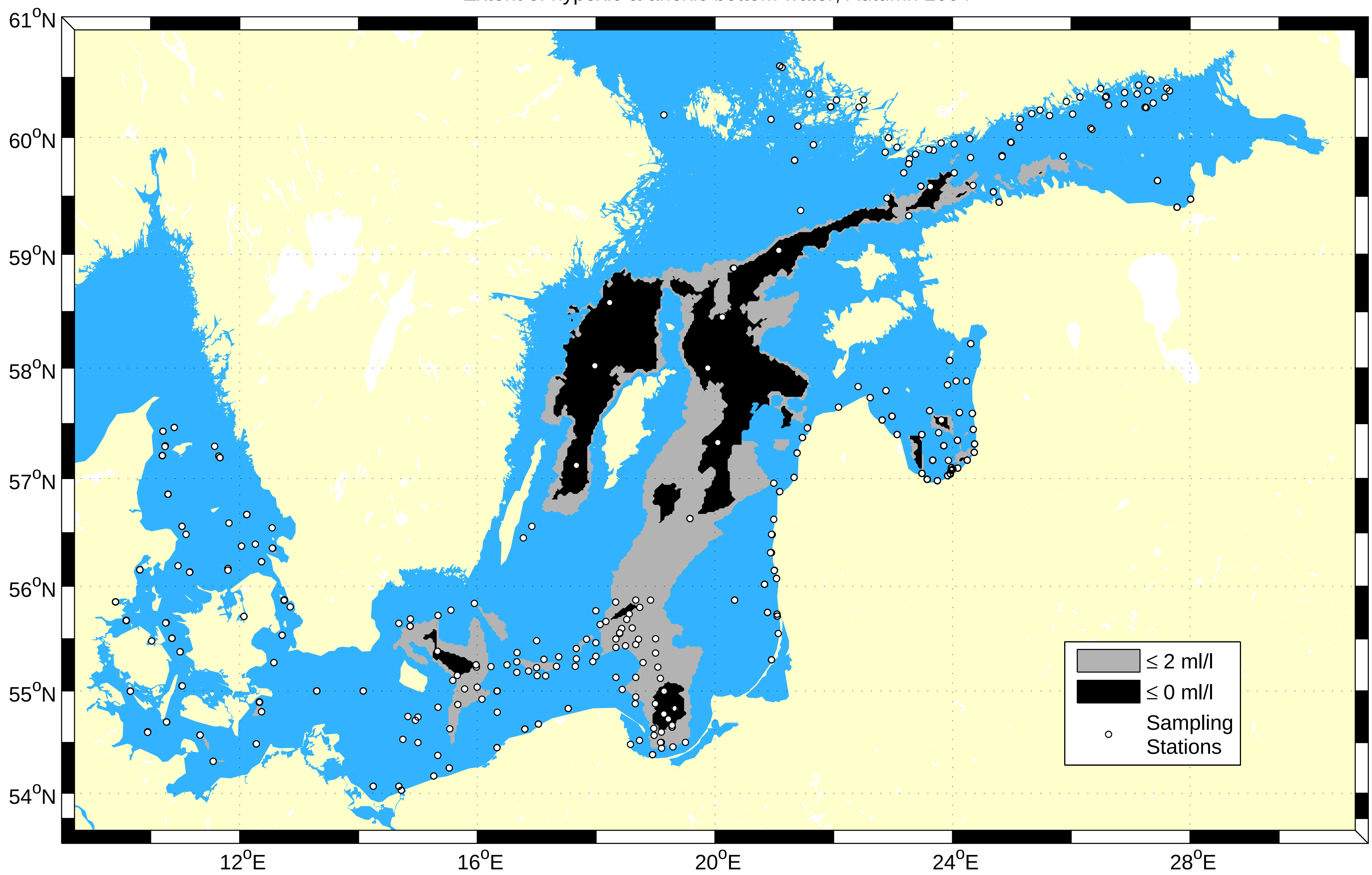


Extent of hypoxic & anoxic bottom water, Autumn 2006

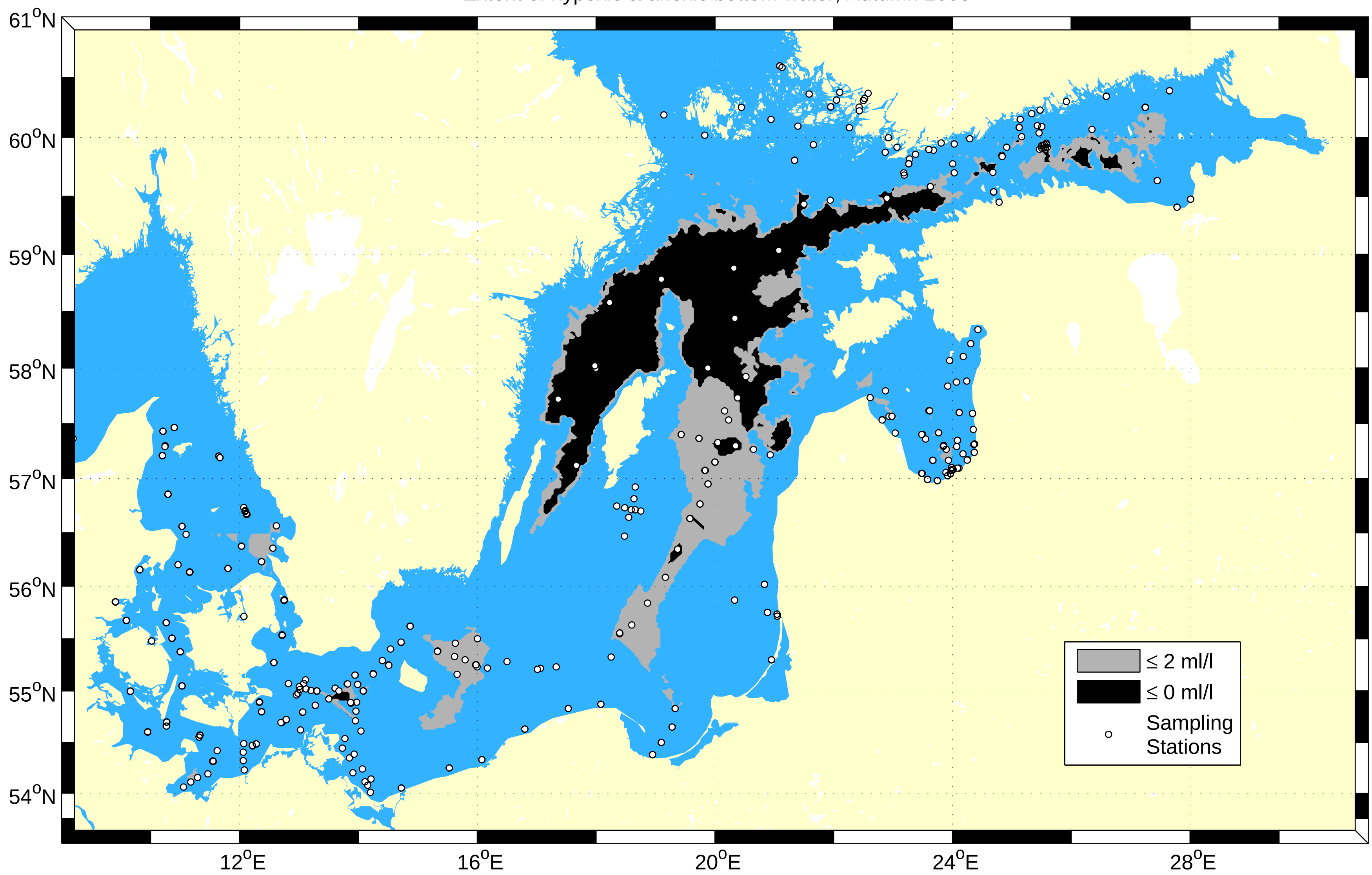



Extent of hypoxic & anoxic bottom water, Autumn 2005
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

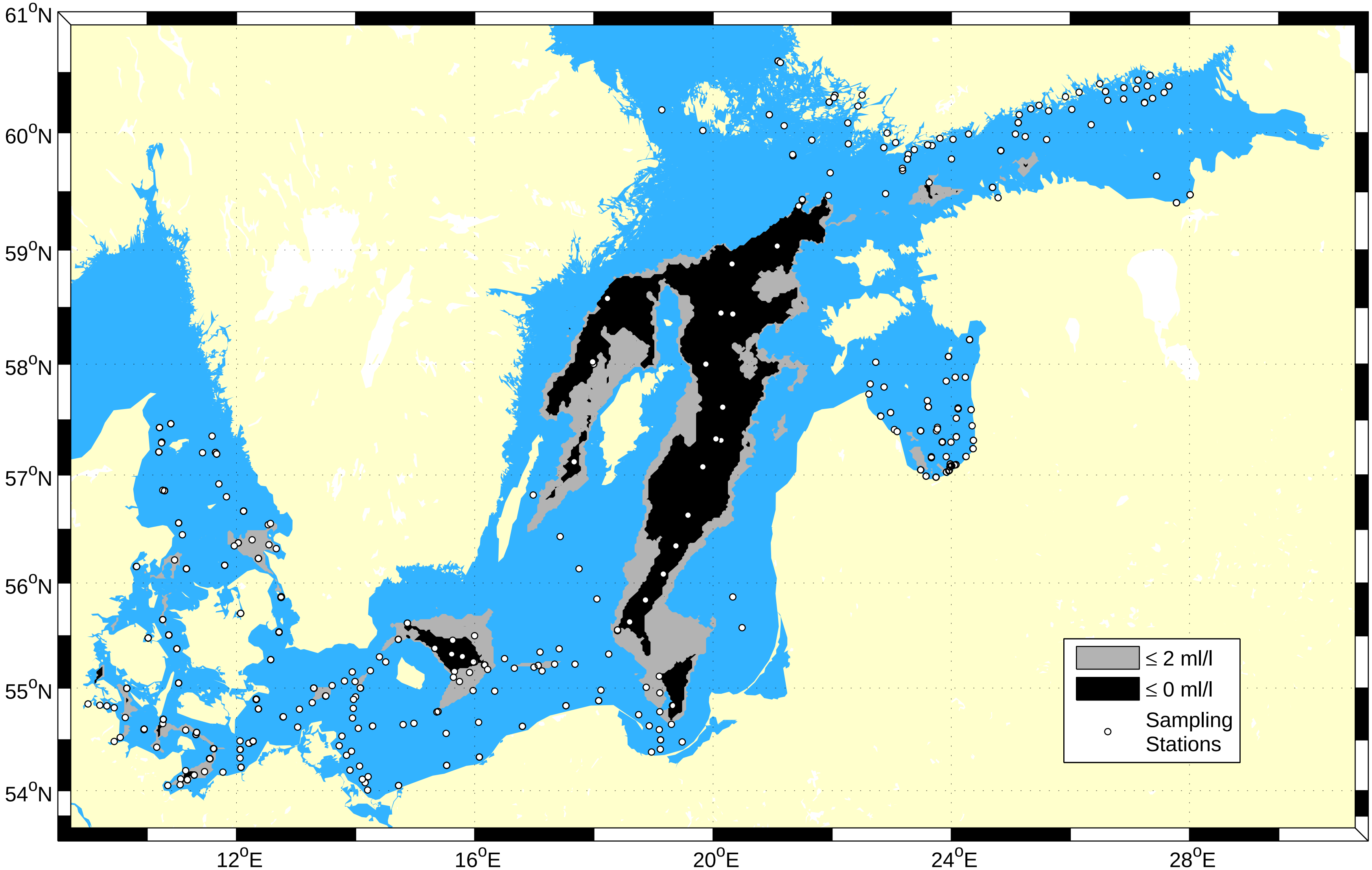
Extent of hypoxic & anoxic bottom water, Autumn 2004



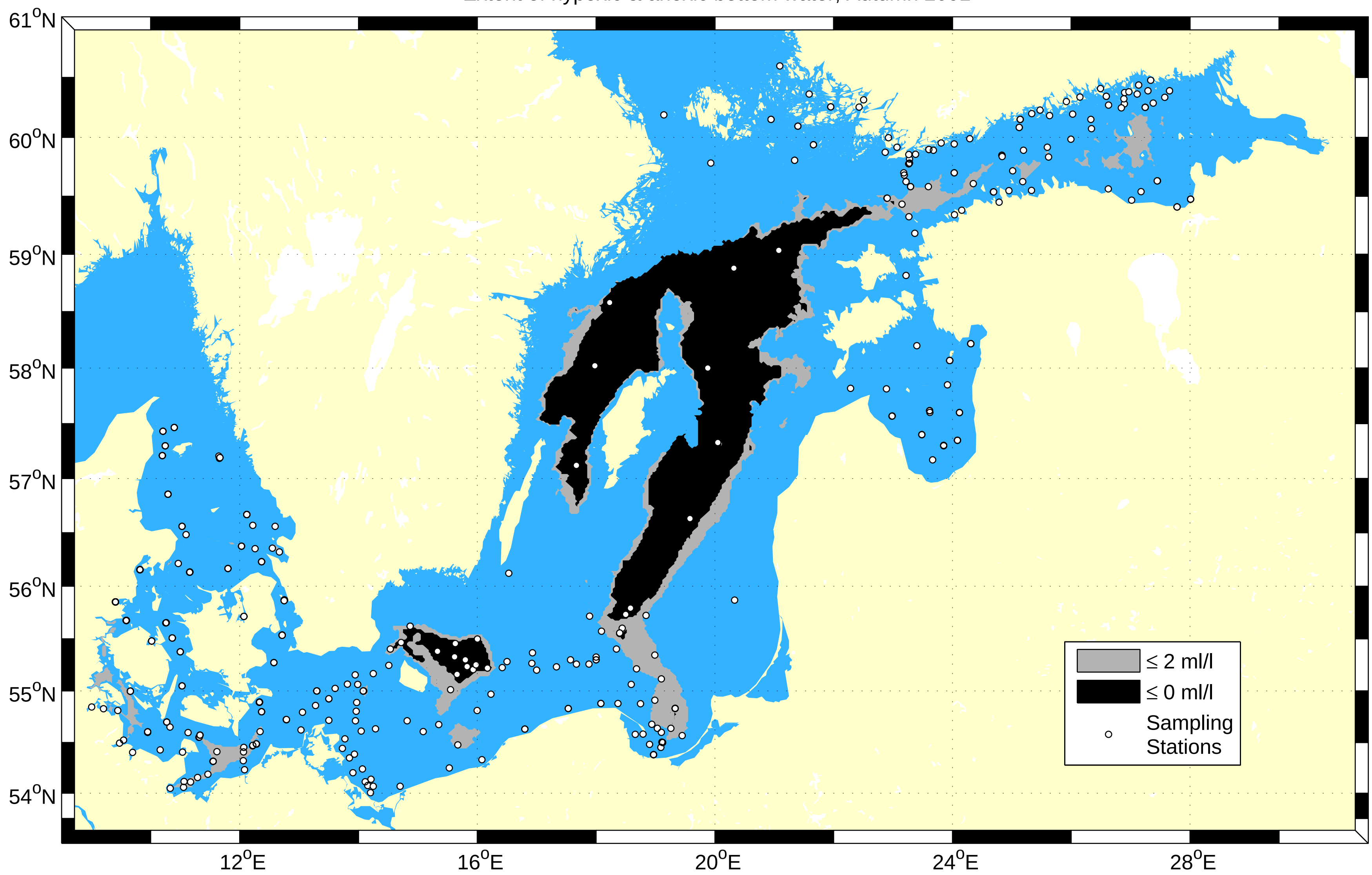
Extent of hypoxic & anoxic bottom water, Autumn 2003

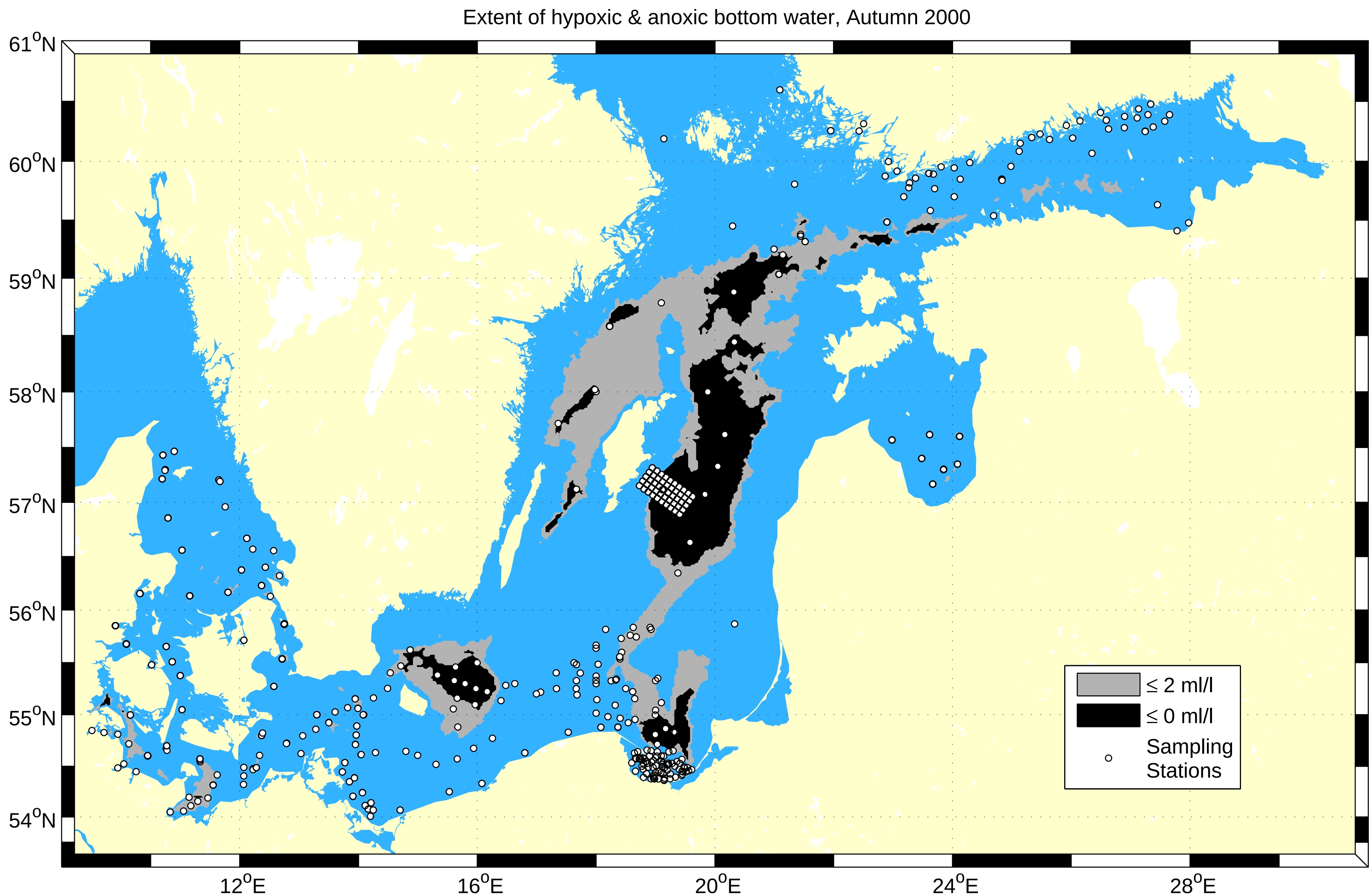


Extent of hypoxic & anoxic bottom water, Autumn 2002

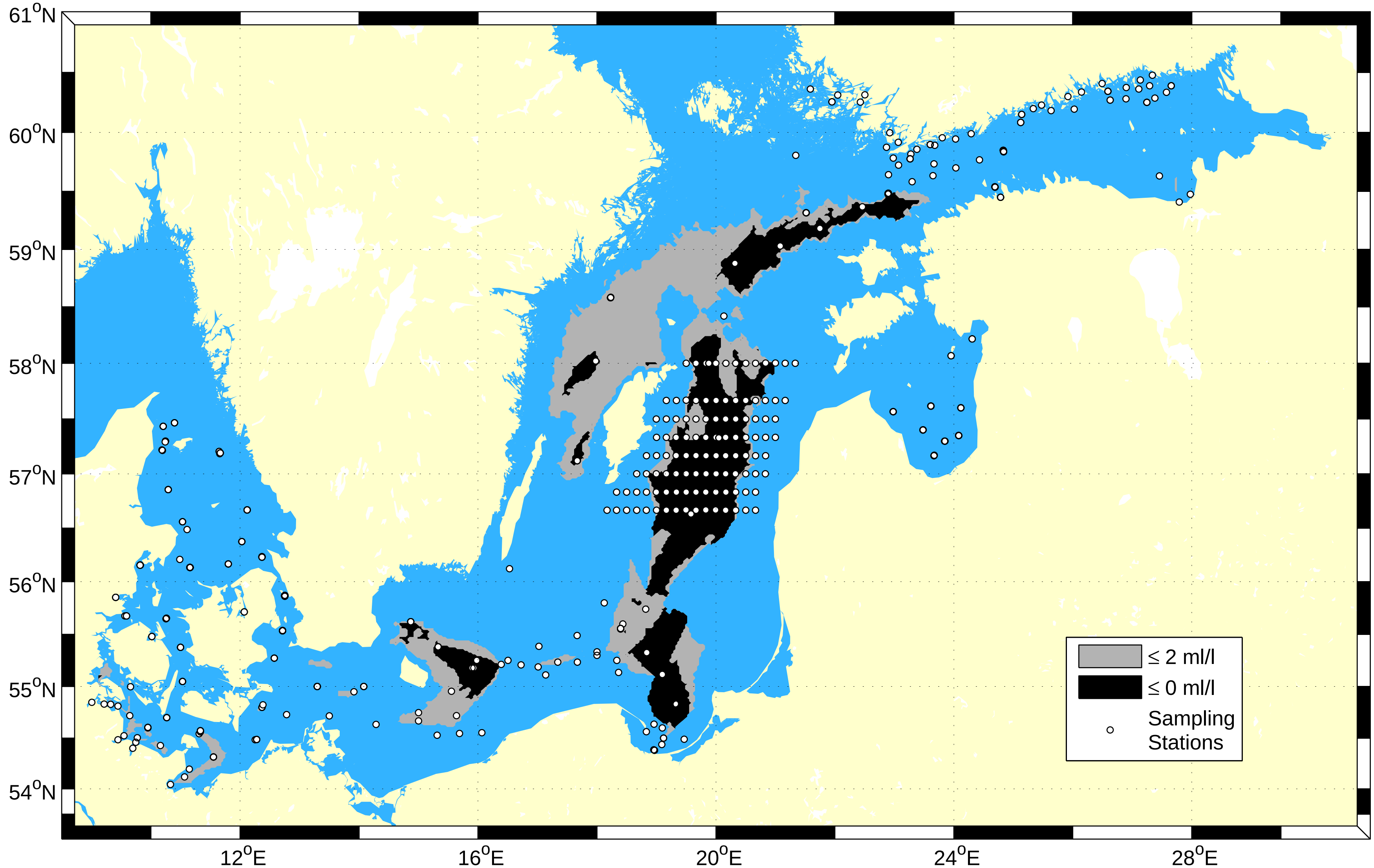


Extent of hypoxic & anoxic bottom water, Autumn 2001

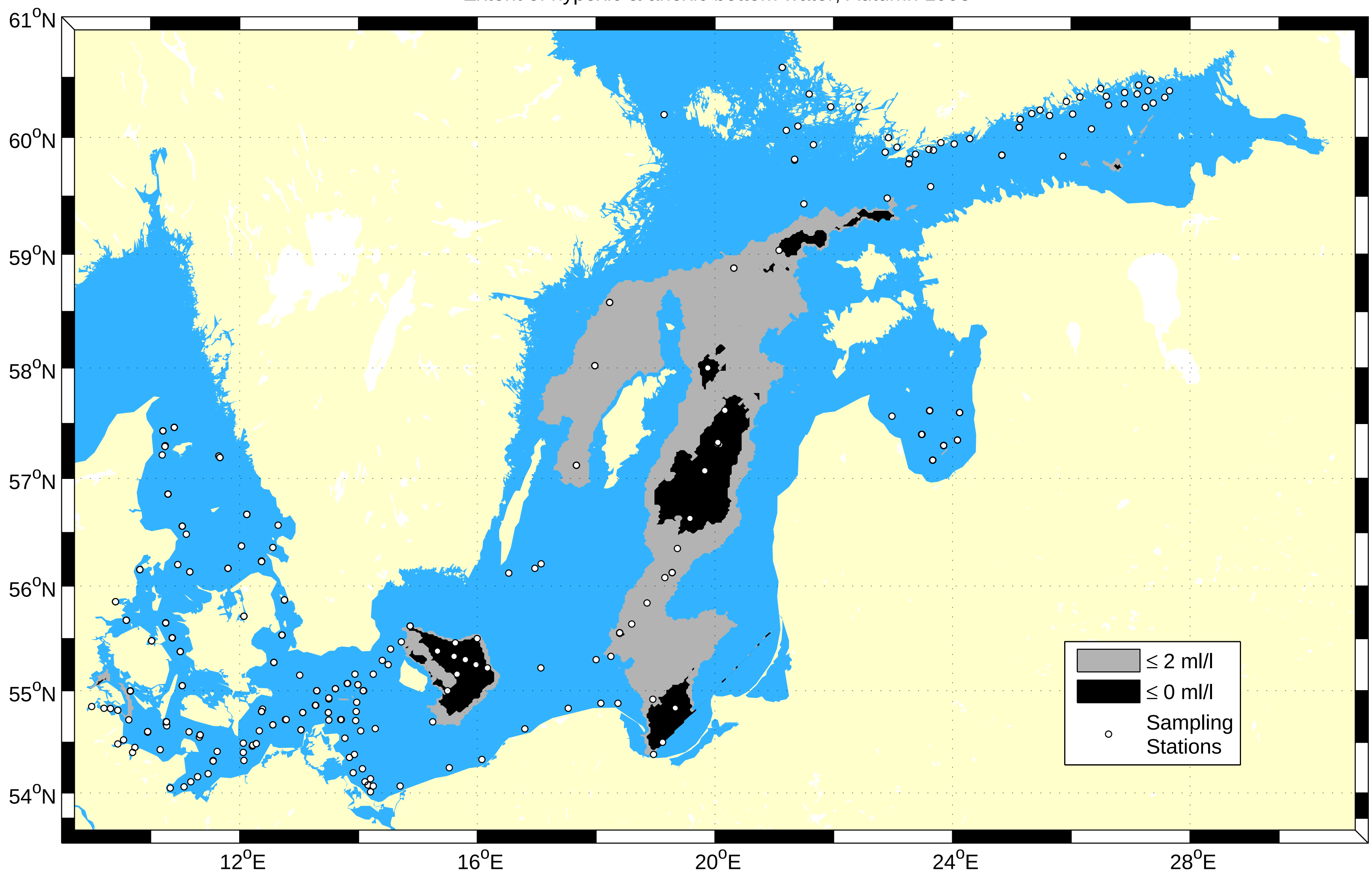



Extent of hypoxic & anoxic bottom water, Autumn 2000
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling
Stations

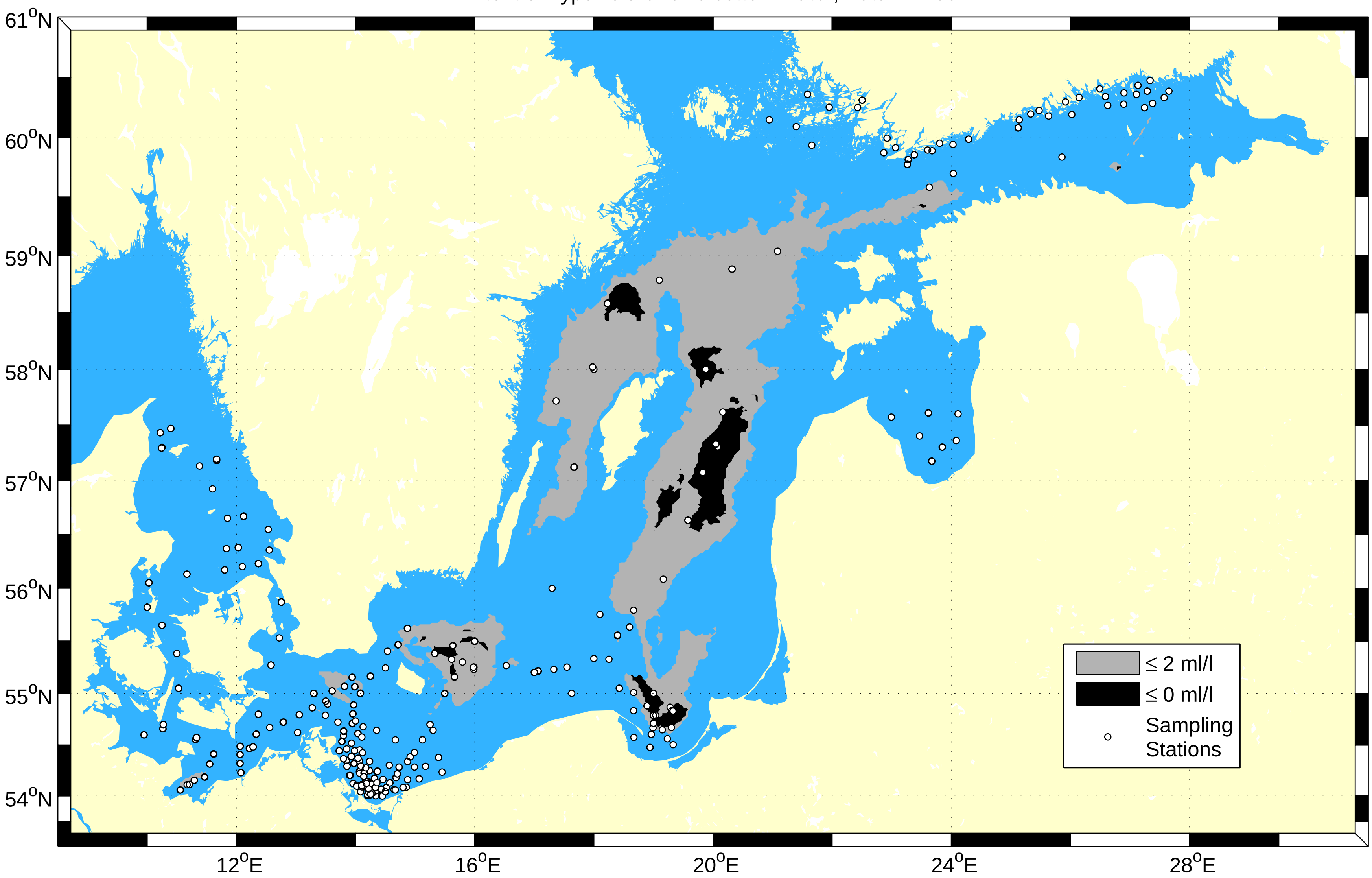
Extent of hypoxic & anoxic bottom water, Autumn 1999



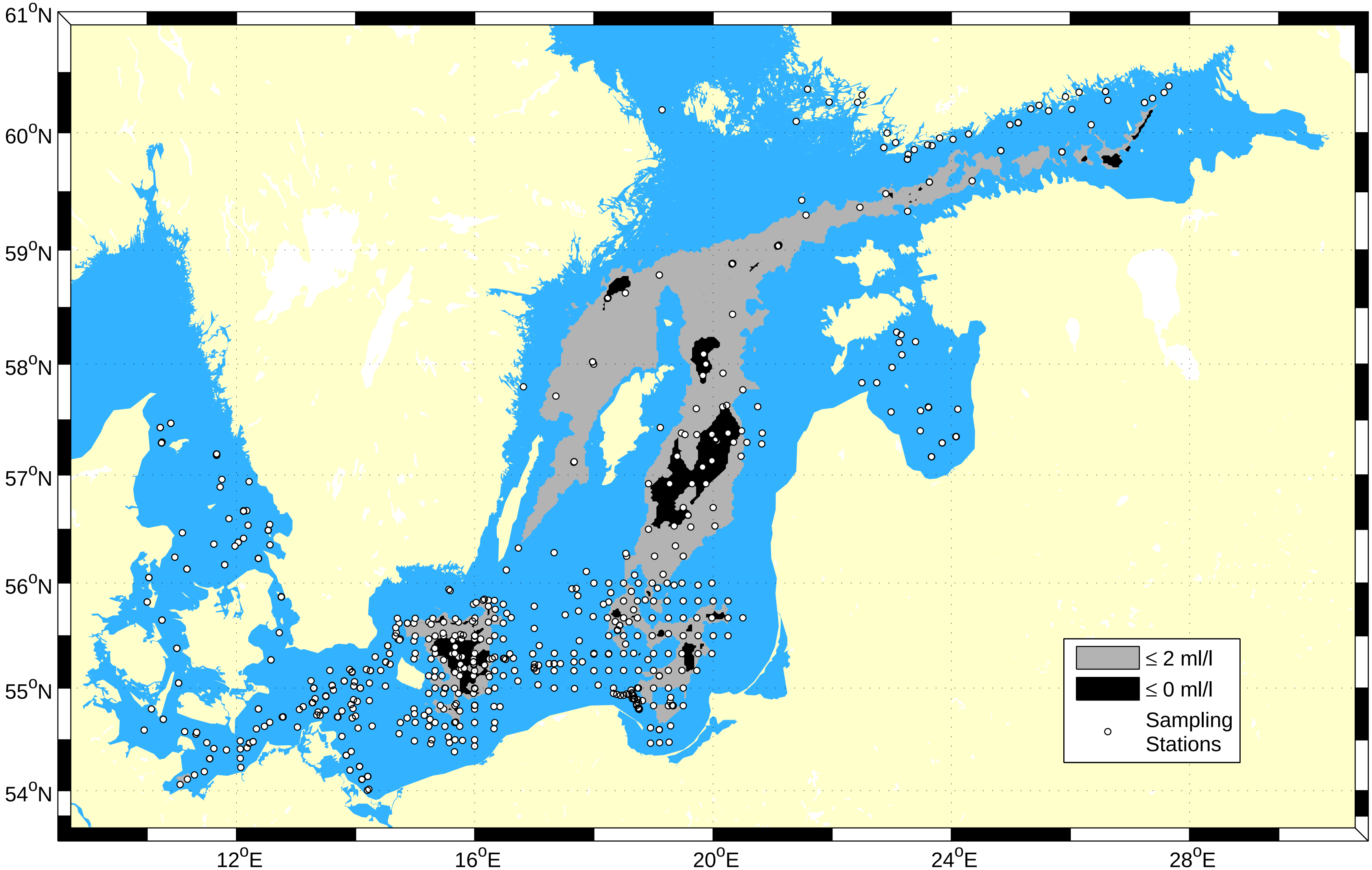
Extent of hypoxic & anoxic bottom water, Autumn 1998

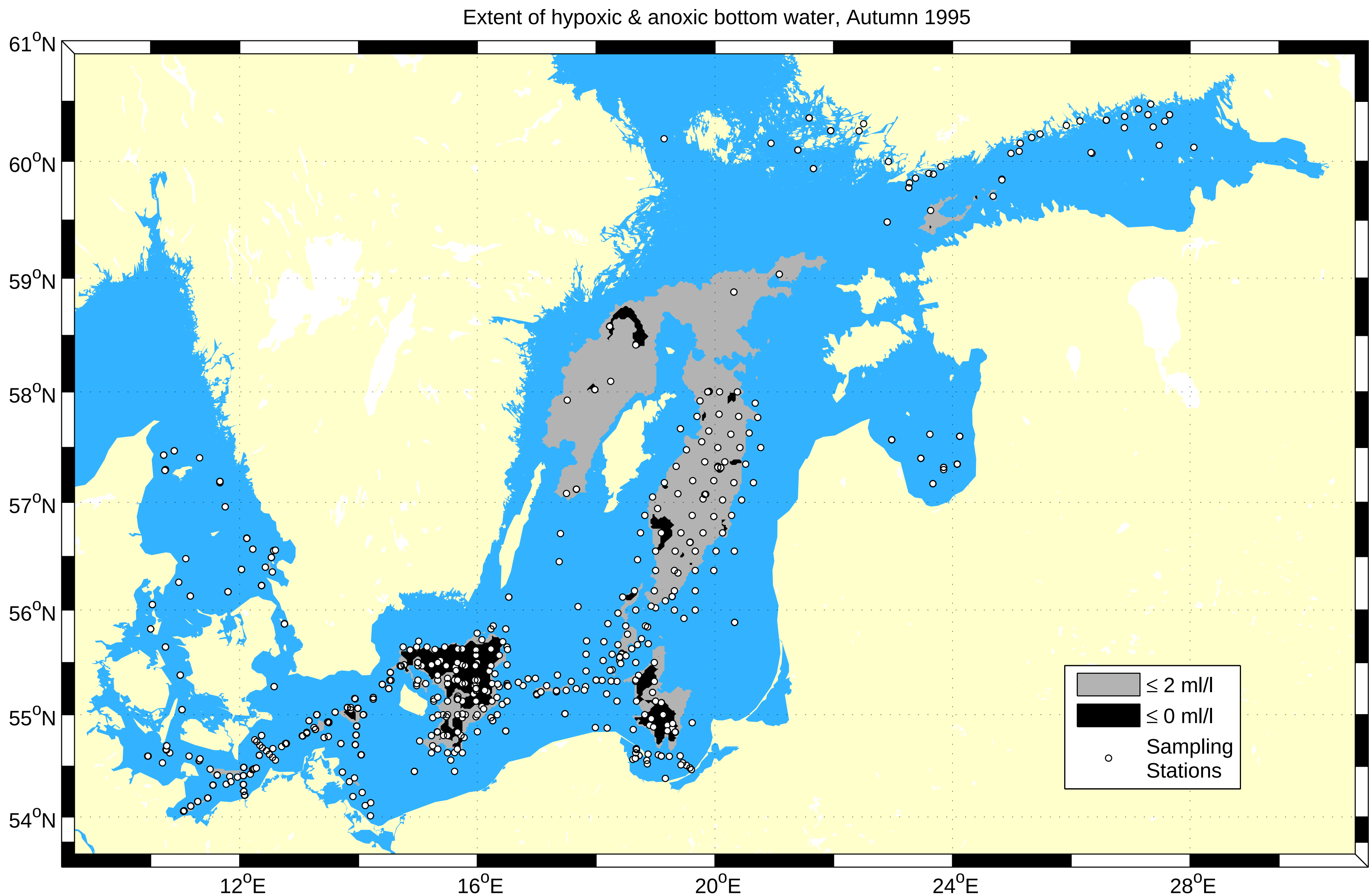


Extent of hypoxic & anoxic bottom water, Autumn 1997

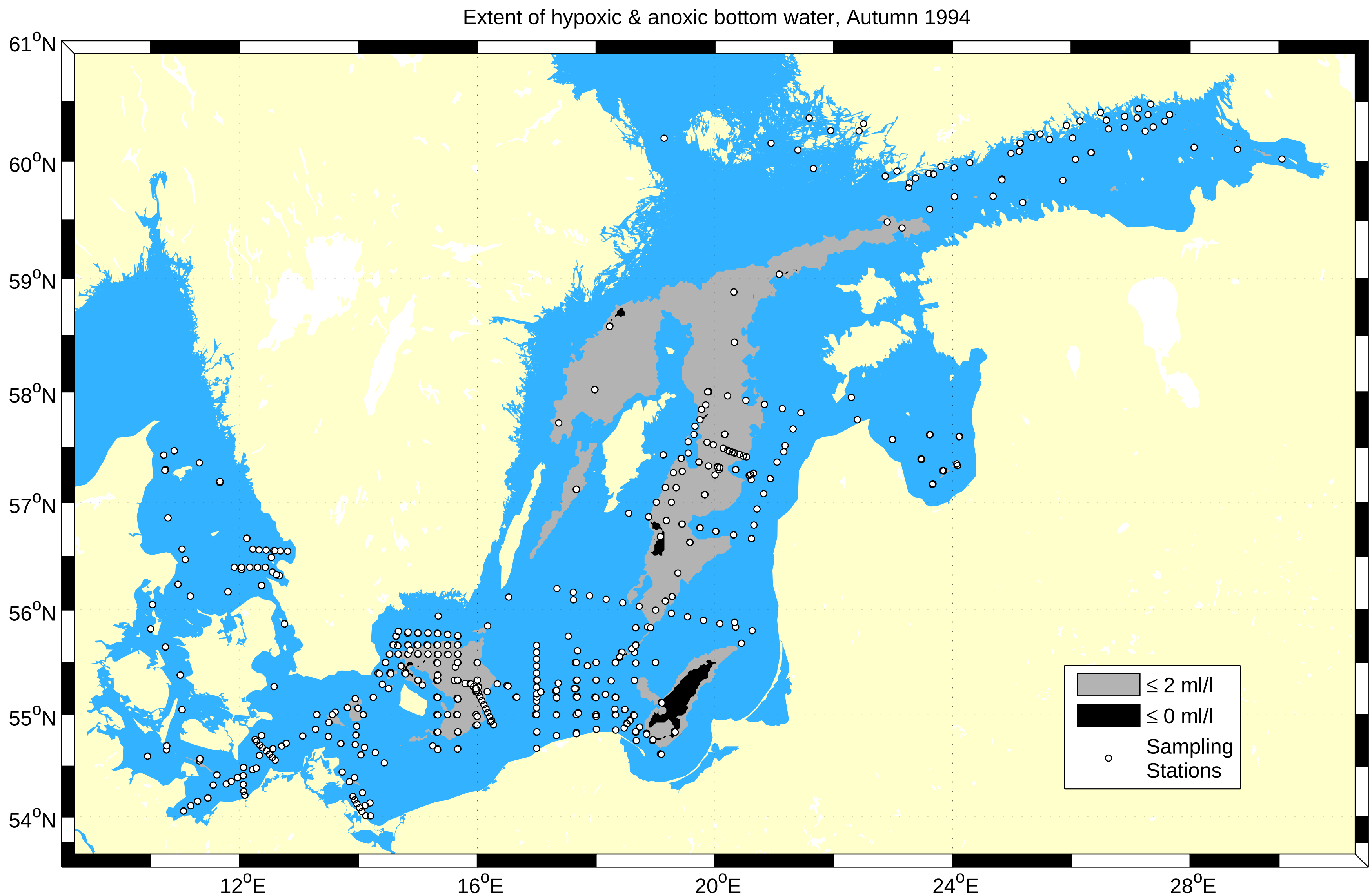


Extent of hypoxic & anoxic bottom water, Autumn 1996





Extent of hypoxic & anoxic bottom water, Autumn 1995
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations


Extent of hypoxic & anoxic bottom water, Autumn 1994
61°N
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59°N
58°N
57°N
56°N
55°N
54°N
12°E
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≤ 2 ml/l
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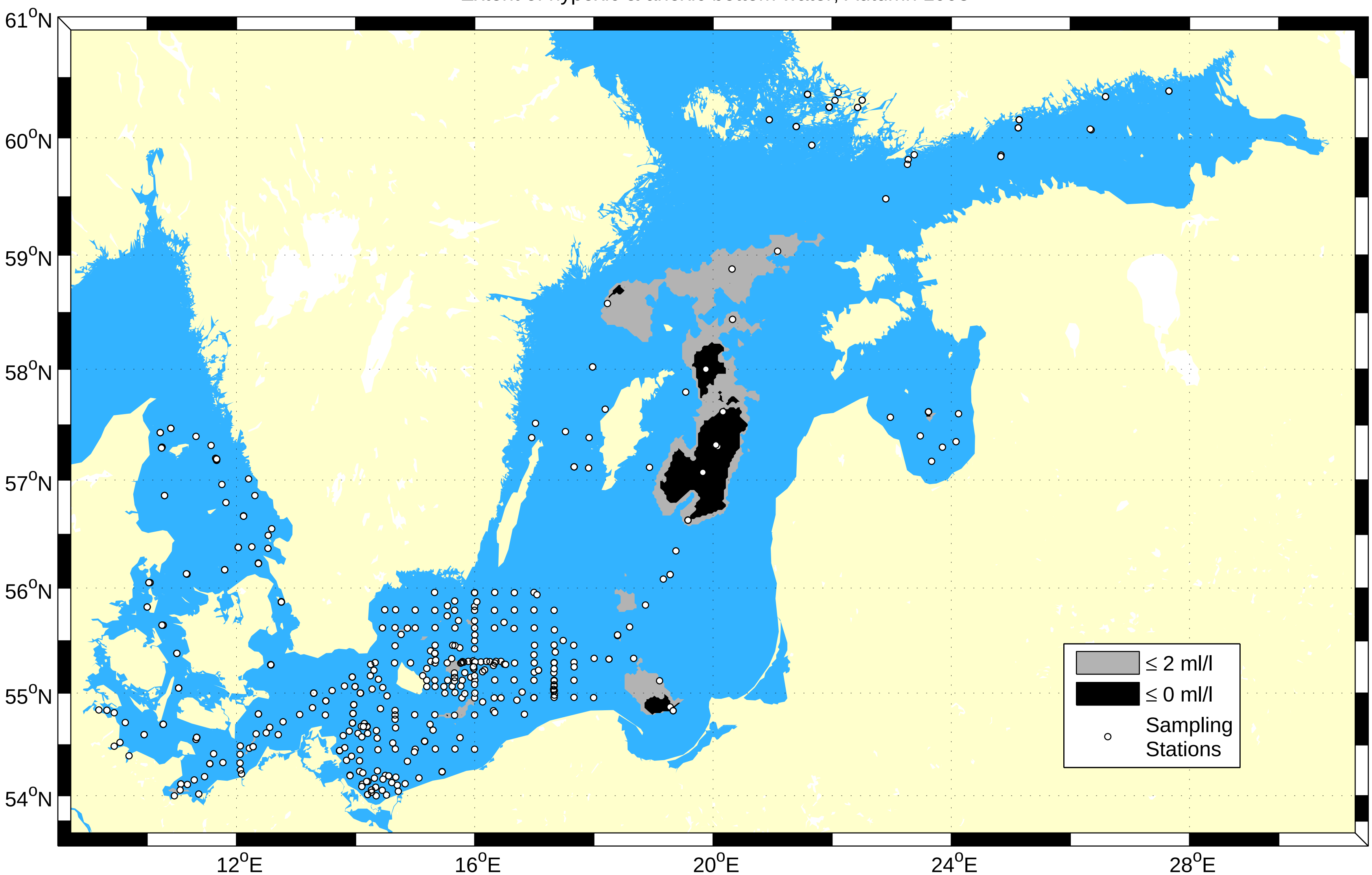
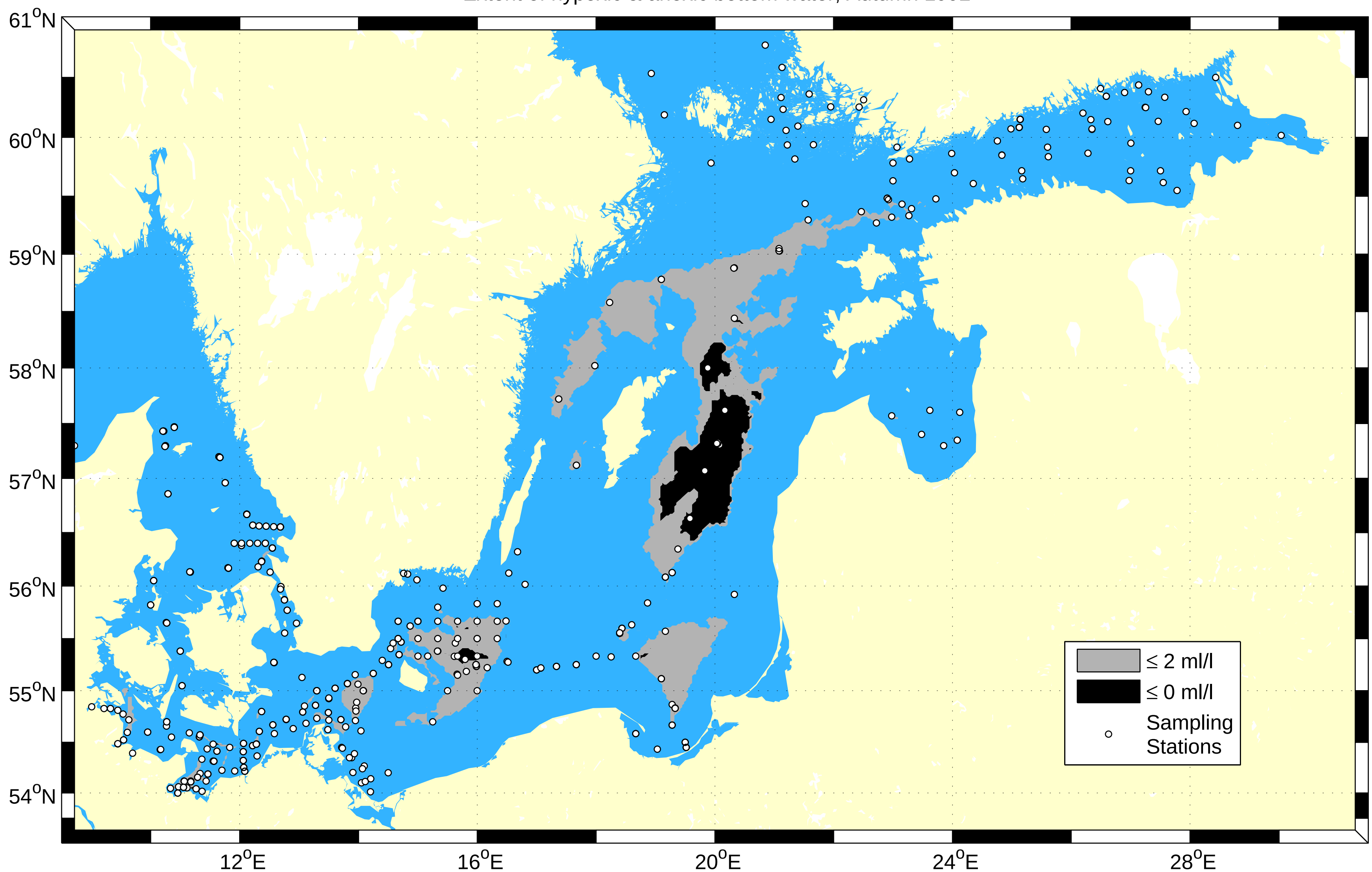
Sampling Stations

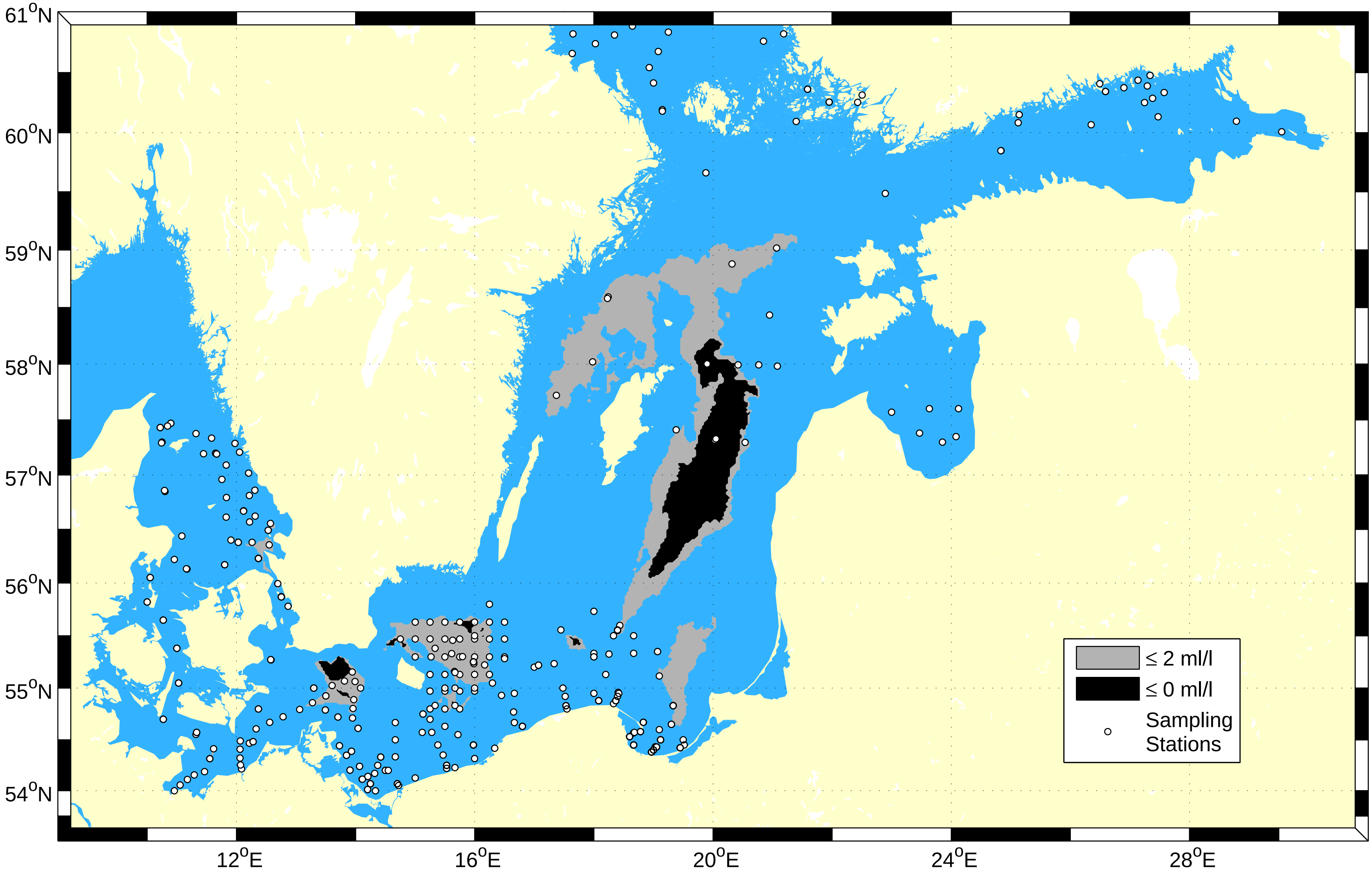
Extent of hypoxic & anoxic bottom water, Autumn 1993



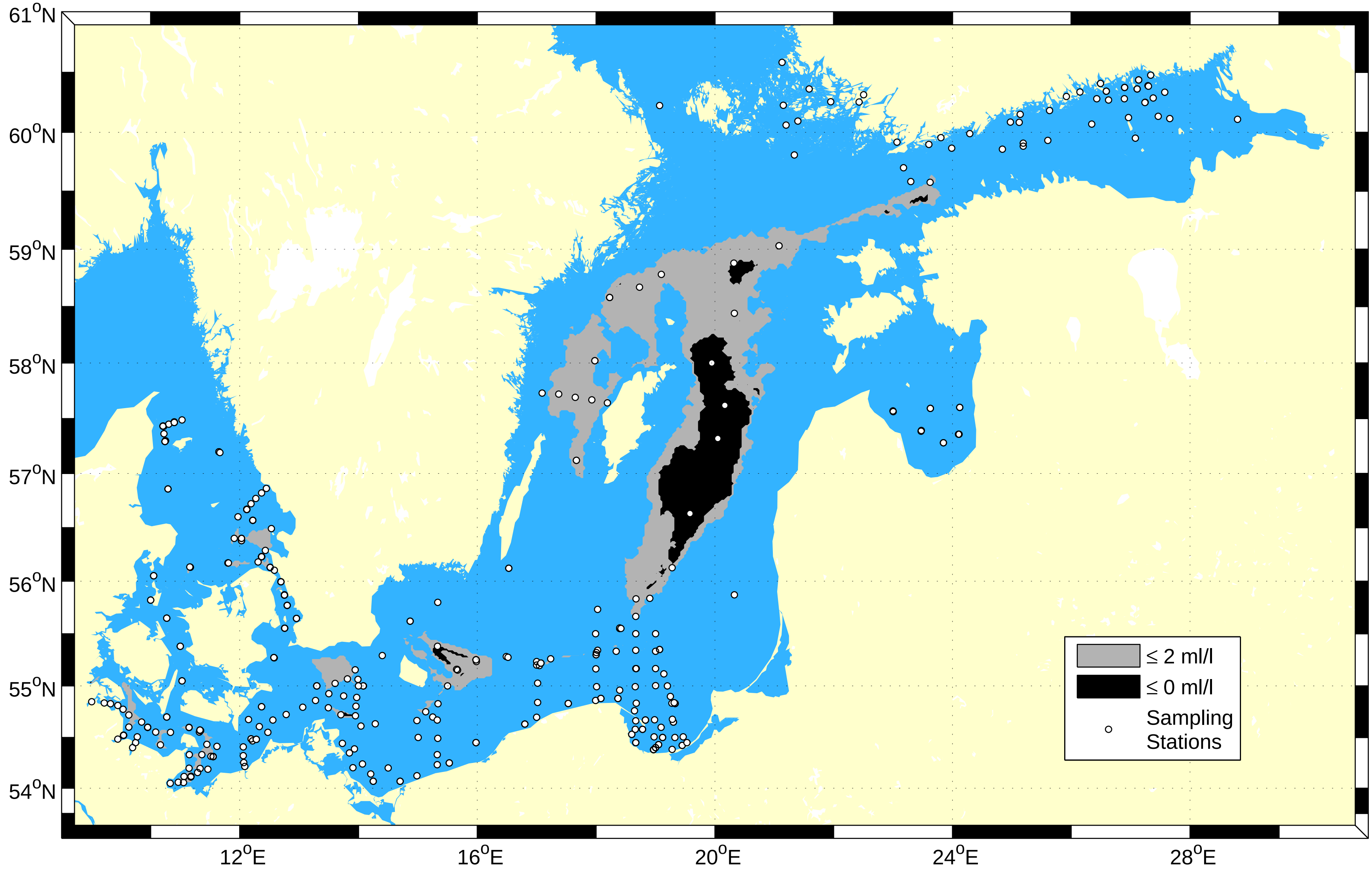
Extent of hypoxic & anoxic bottom water, Autumn 1992

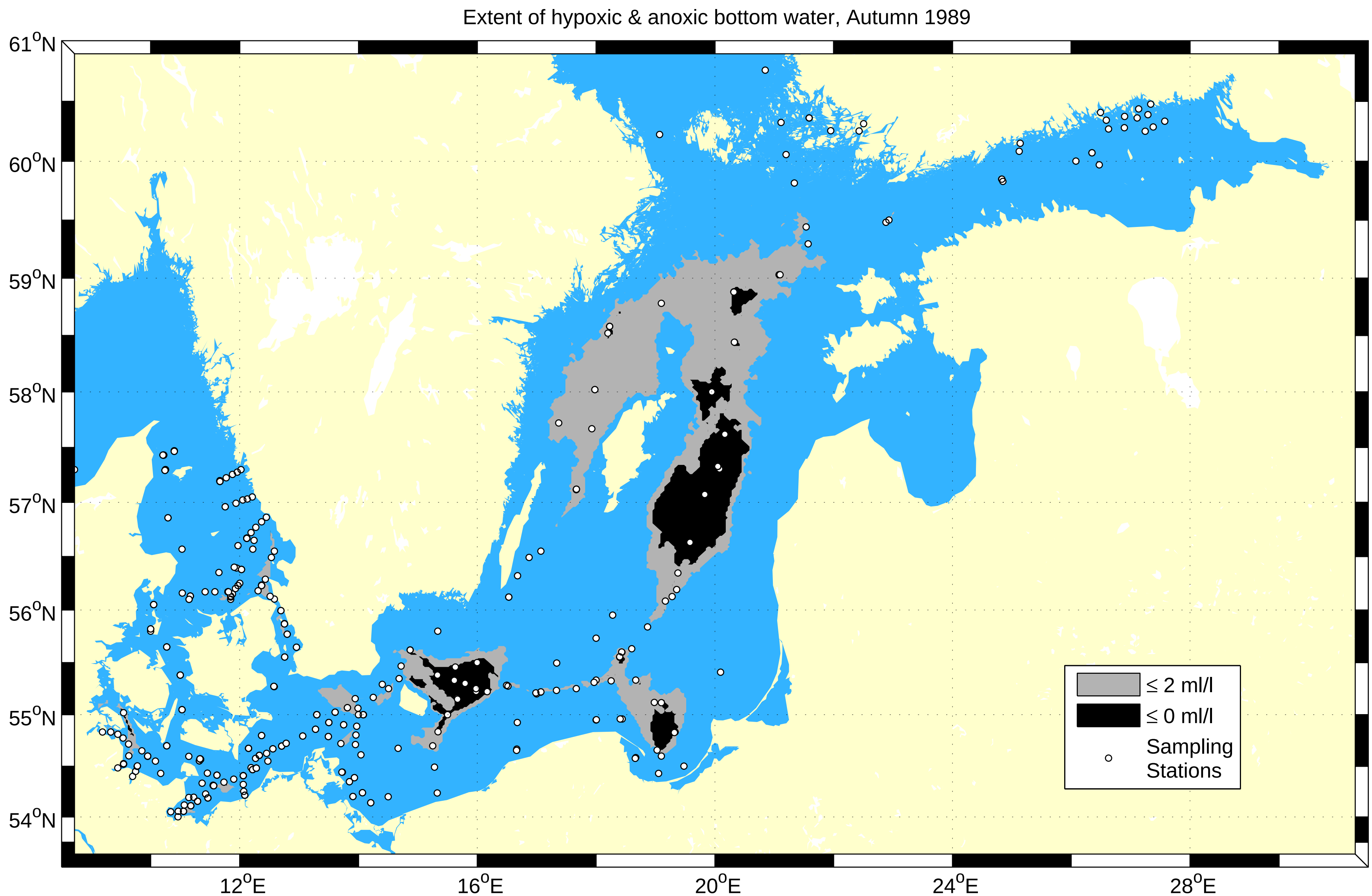


Extent of hypoxic & anoxic bottom water, Autumn 1991

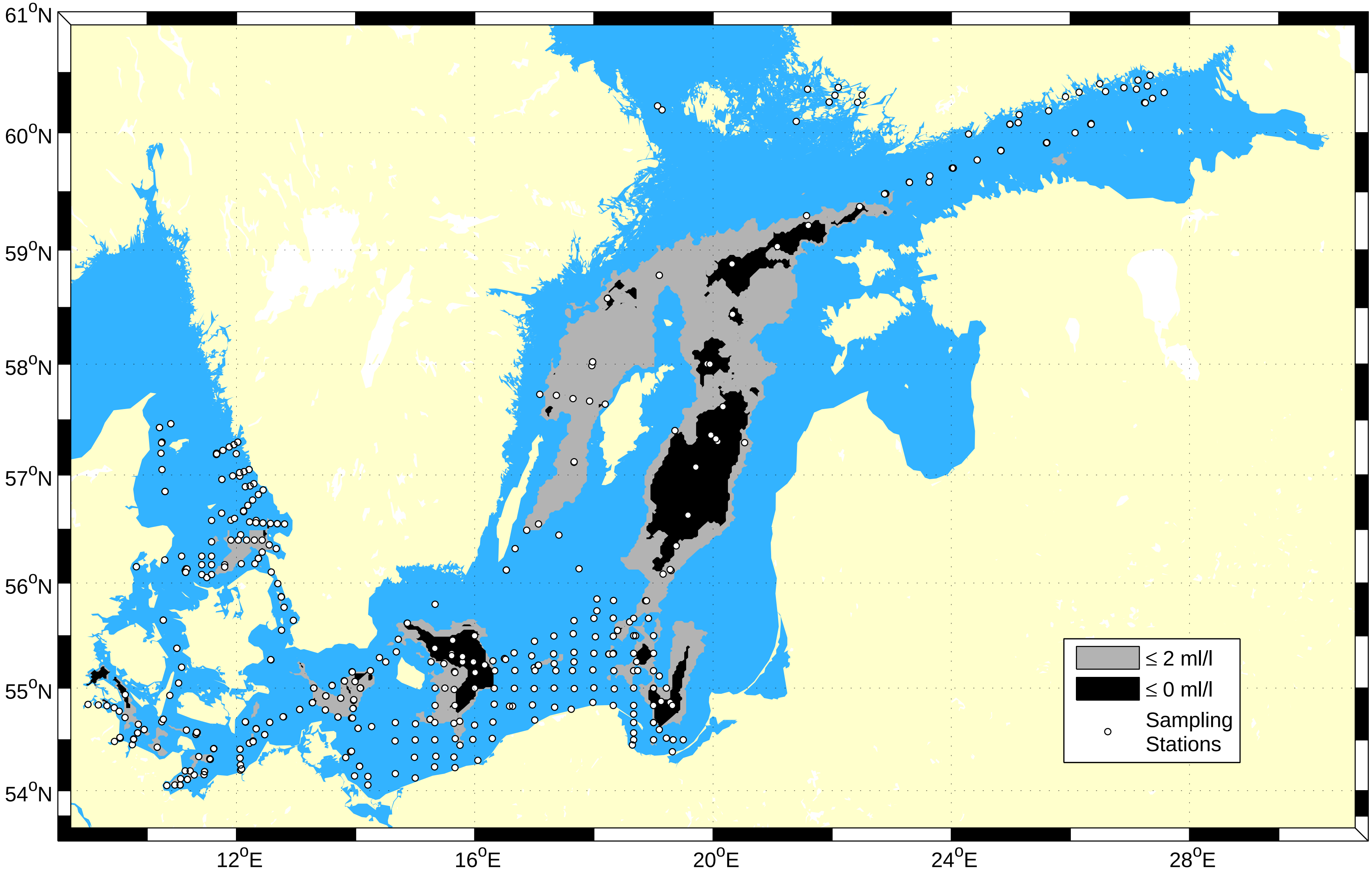


Extent of hypoxic & anoxic bottom water, Autumn 1990

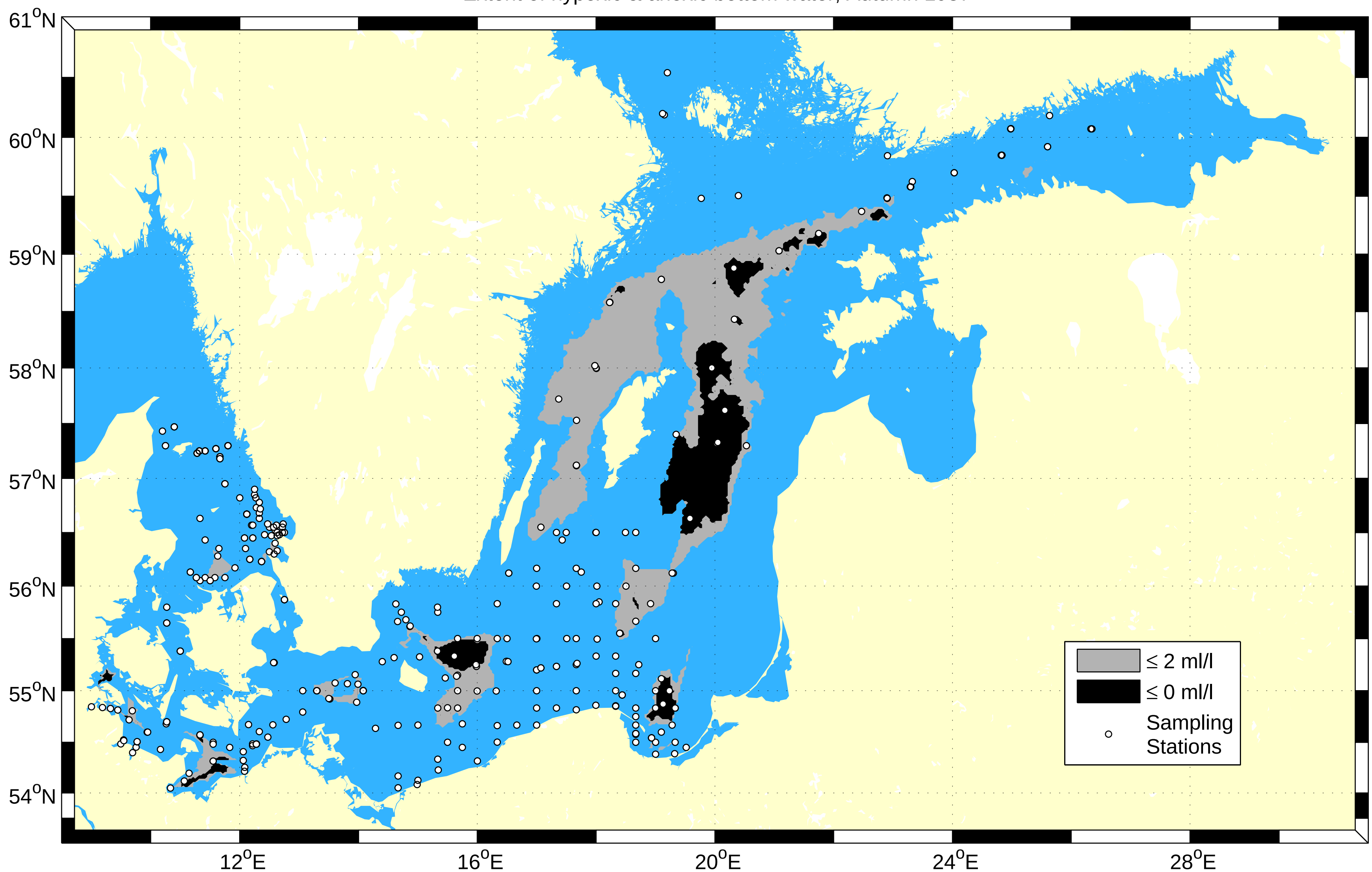


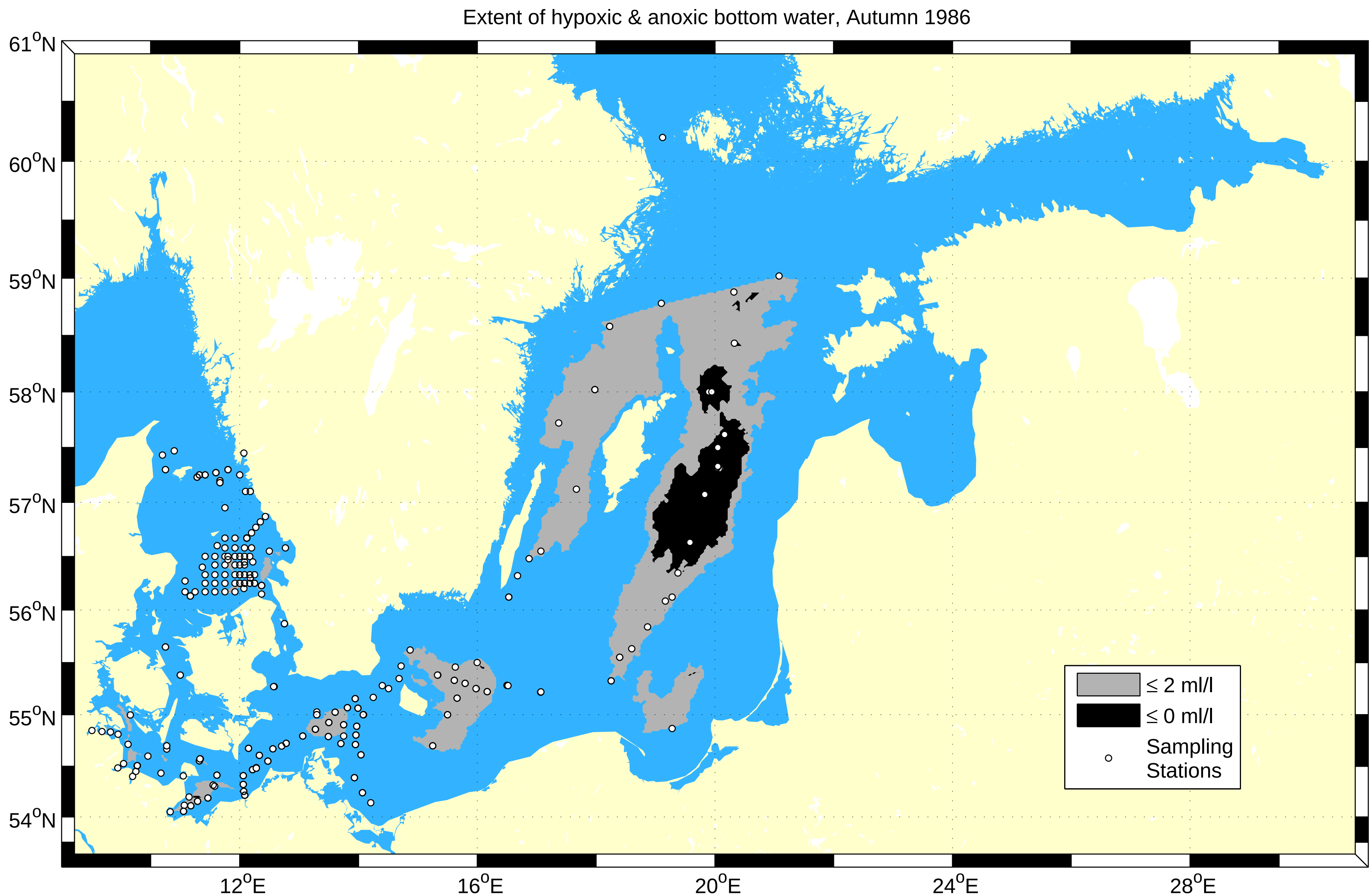

Extent of hypoxic & anoxic bottom water, Autumn 1989
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

Extent of hypoxic & anoxic bottom water, Autumn 1988



Extent of hypoxic & anoxic bottom water, Autumn 1987




Extent of hypoxic & anoxic bottom water, Autumn 1986
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
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16°E
20°E
24°E
28°E
≤ 2 ml/l
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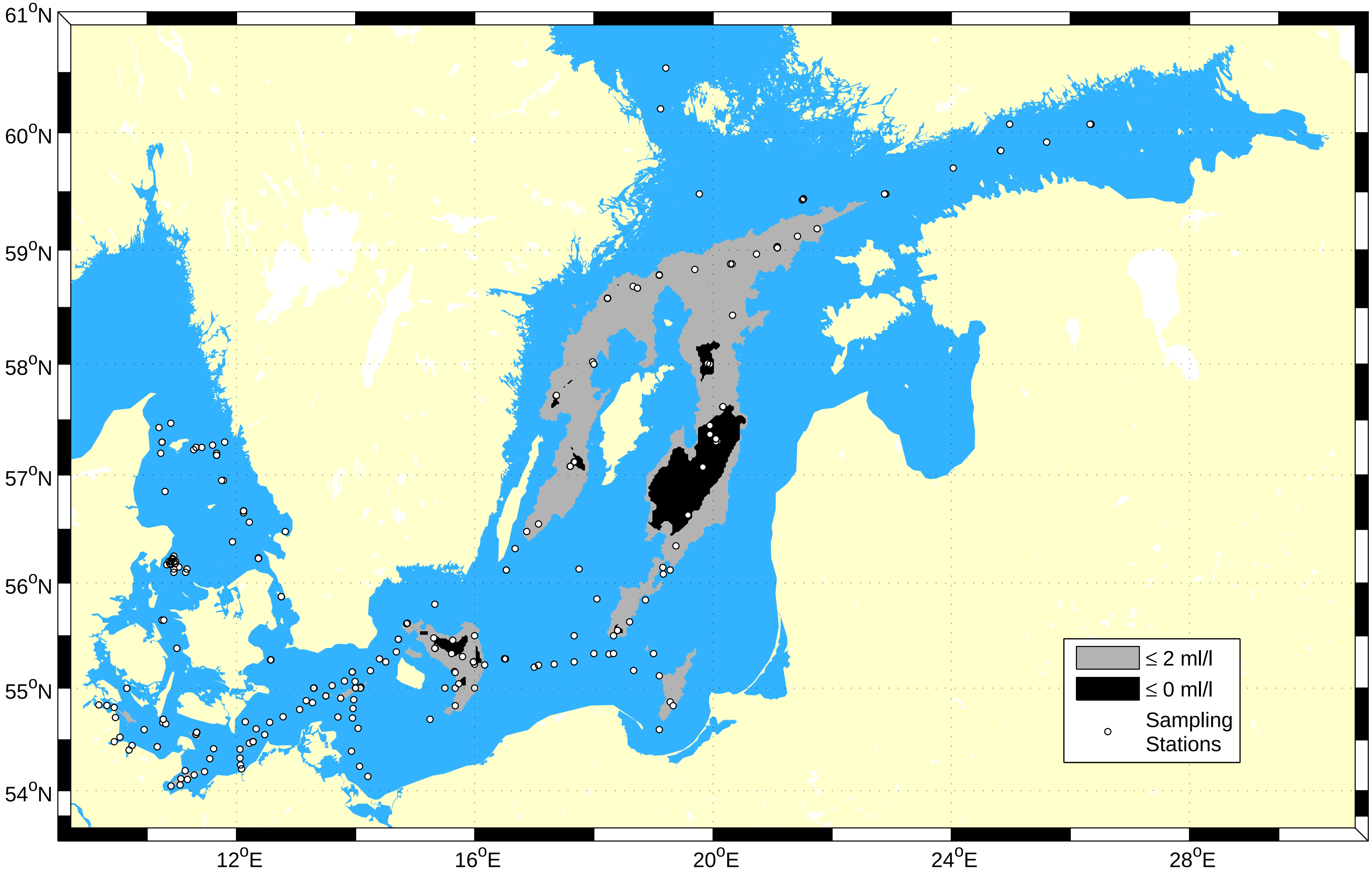
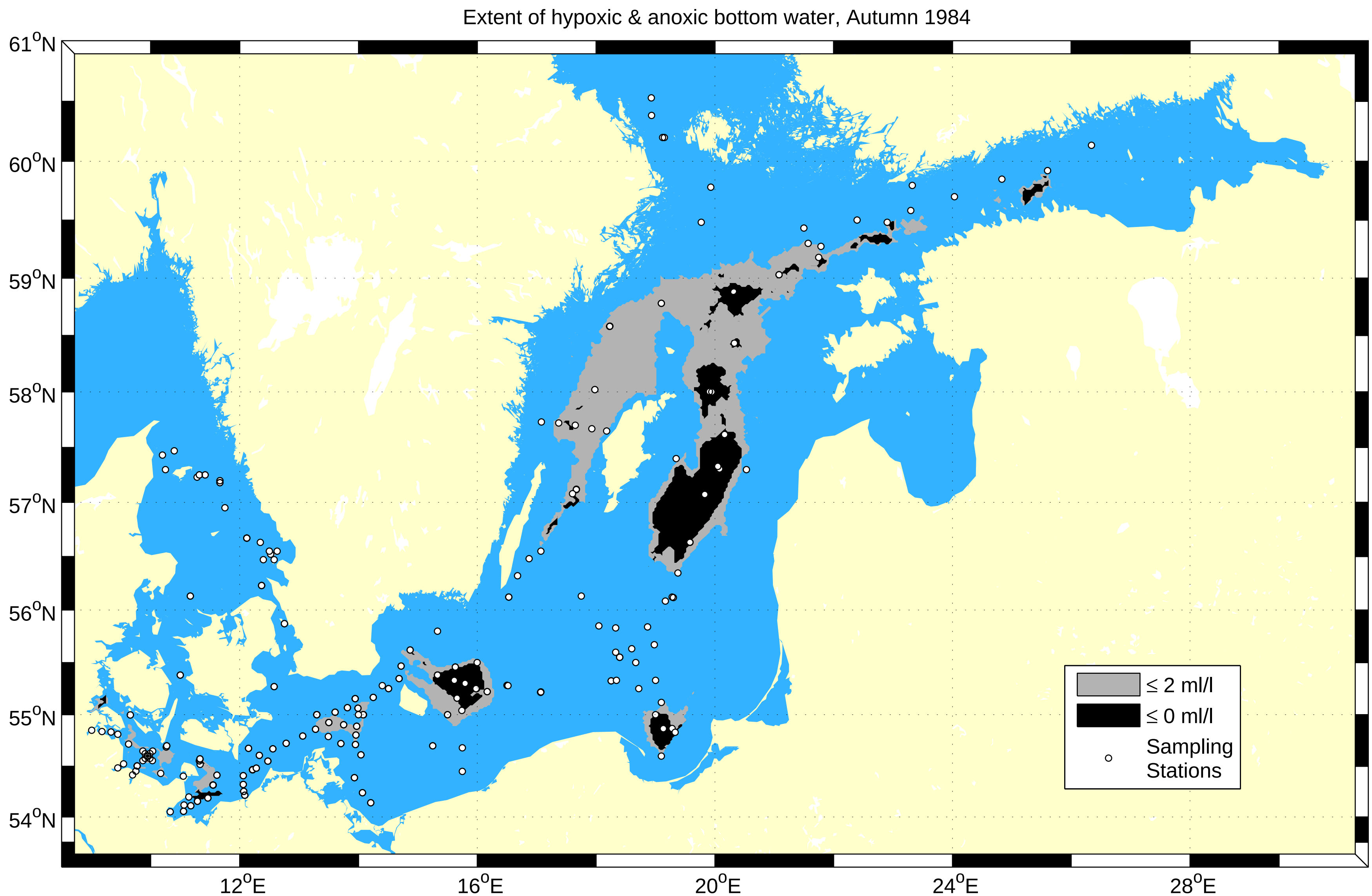
Sampling Stations

Extent of hypoxic & anoxic bottom water, Autumn 1985





Extent of hypoxic & anoxic bottom water, Autumn 1984
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60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
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≤ 2 ml/l
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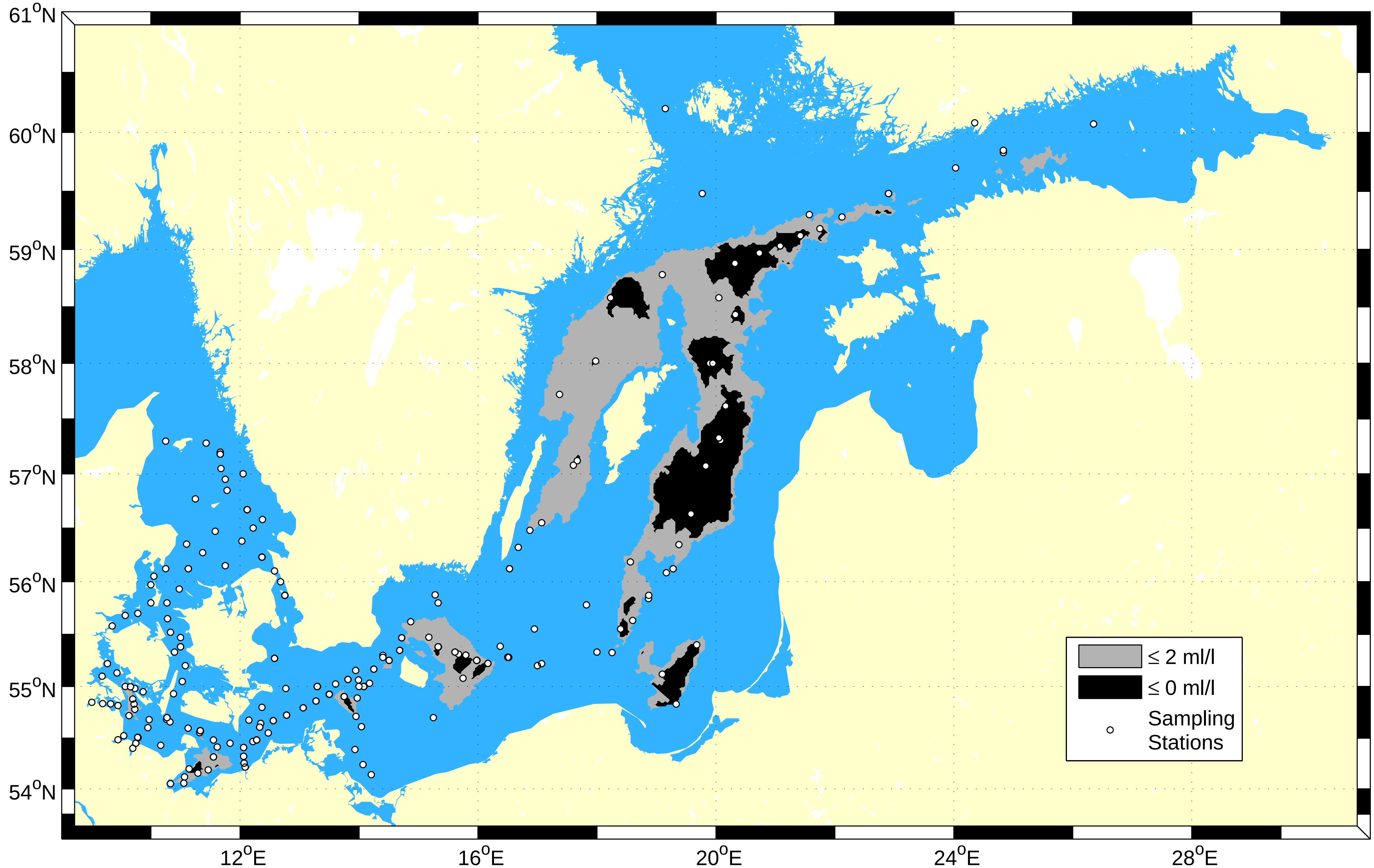
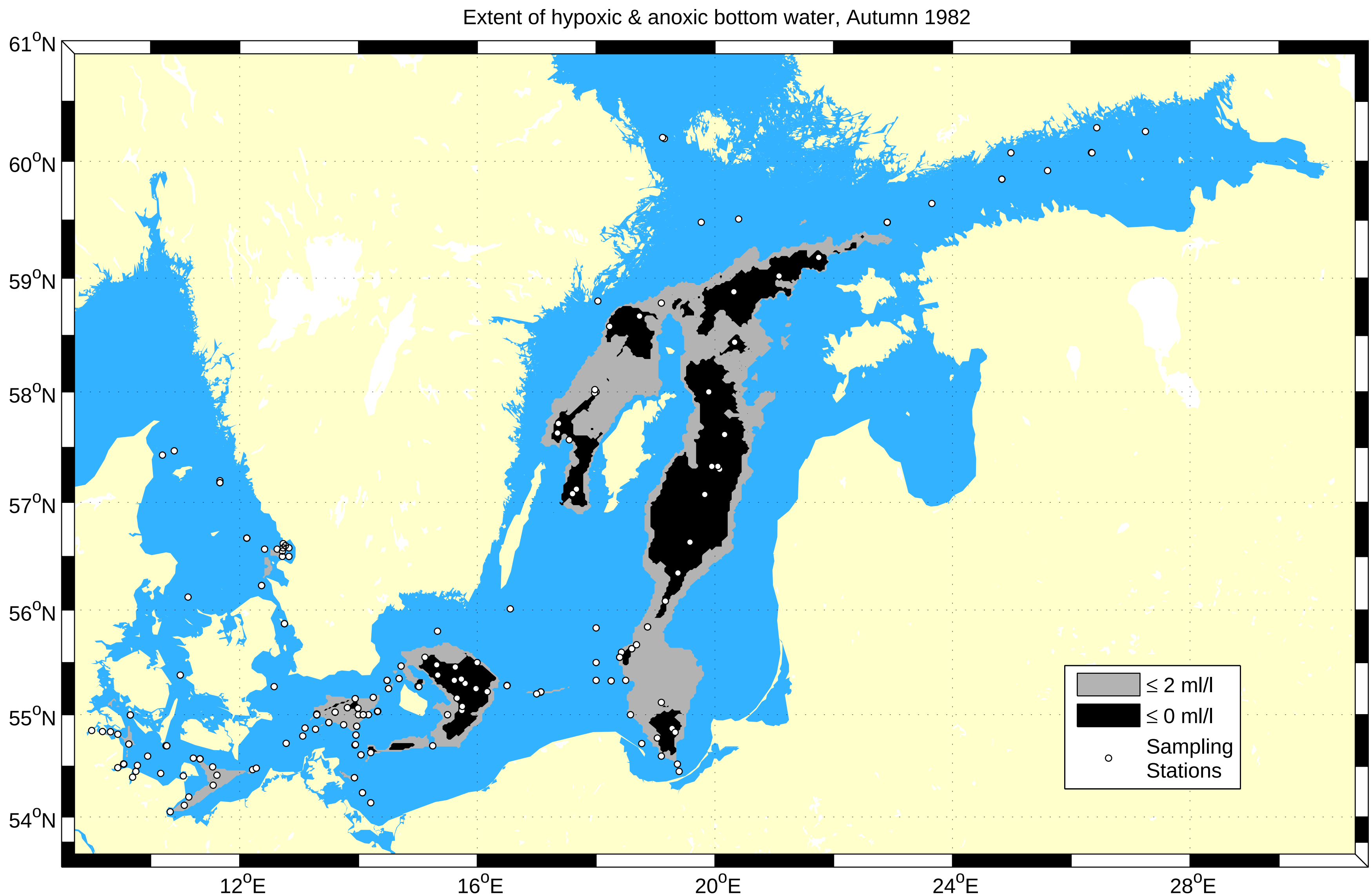
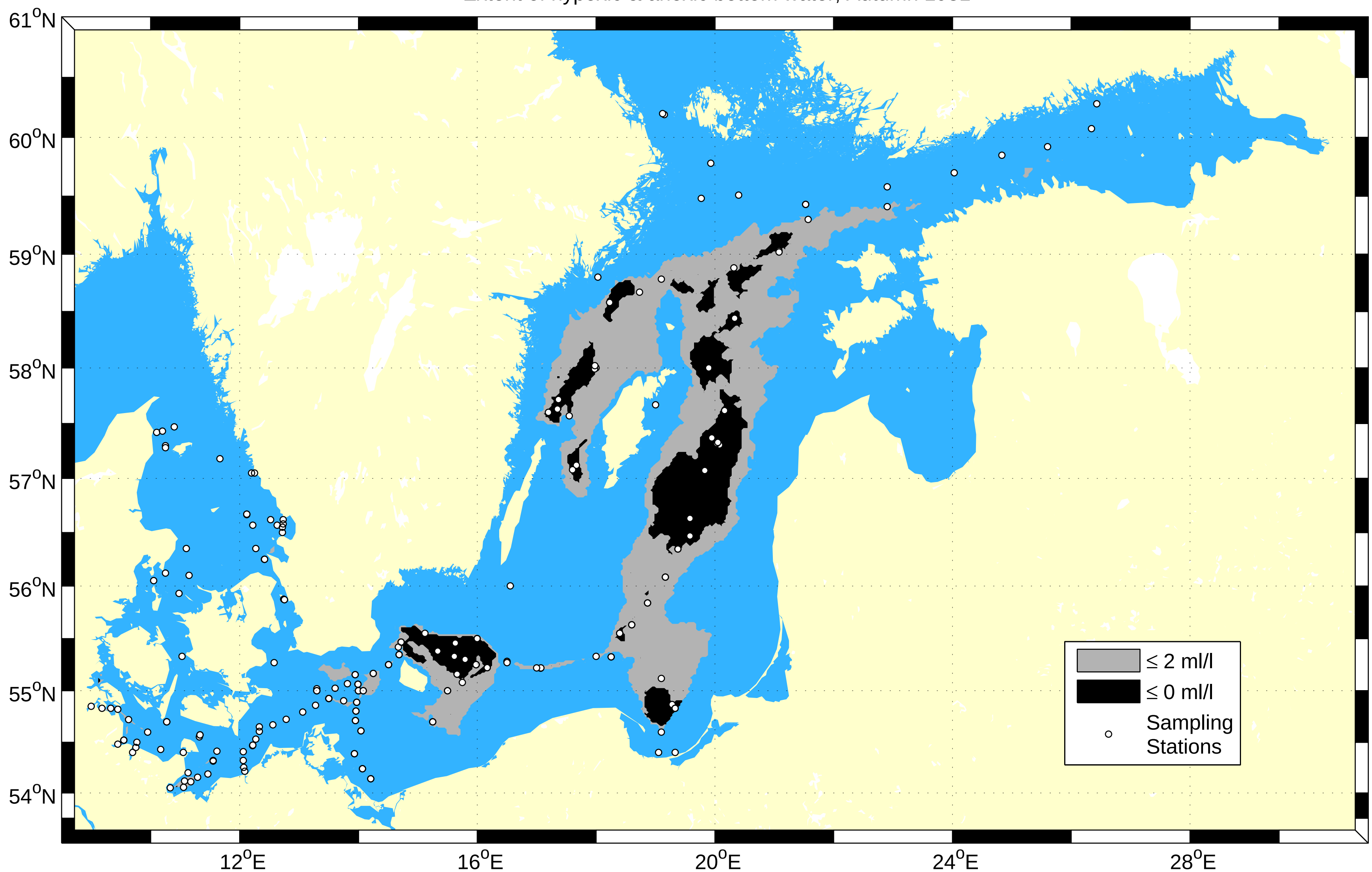
Sampling Stations

Extent of hypoxic & anoxic bottom water, Autumn 1983

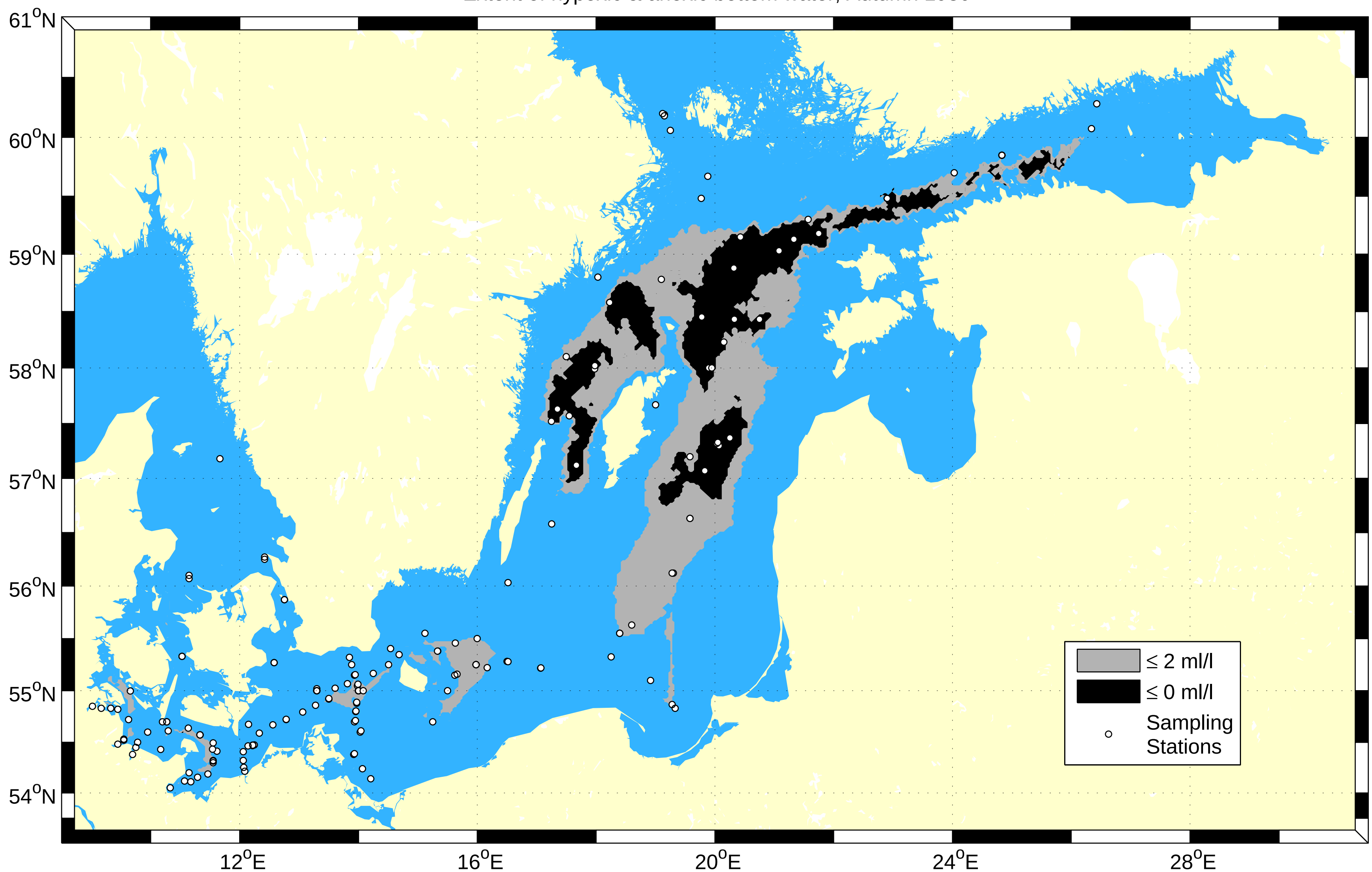



Extent of hypoxic & anoxic bottom water, Autumn 1982
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

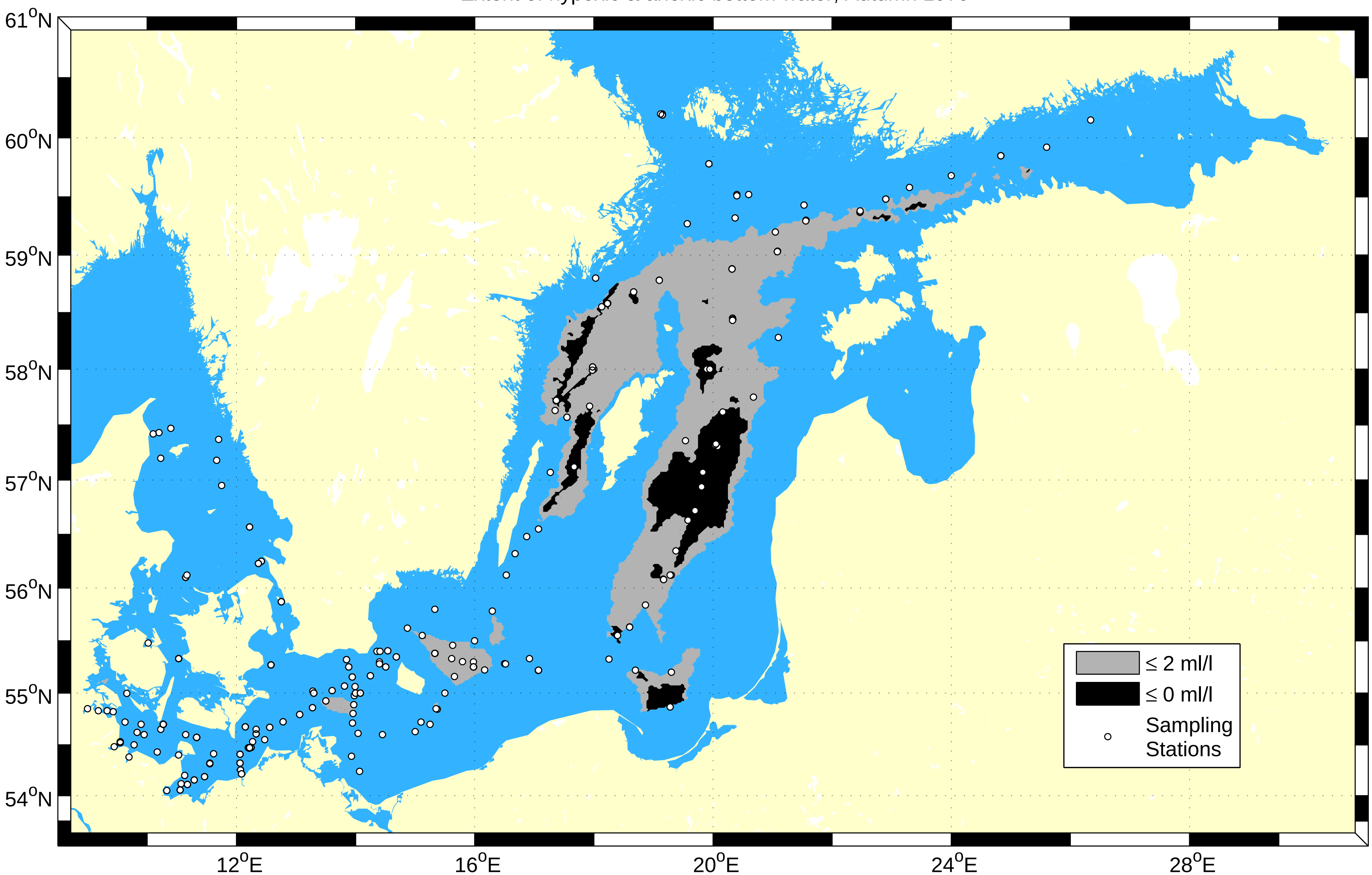
Extent of hypoxic & anoxic bottom water, Autumn 1981



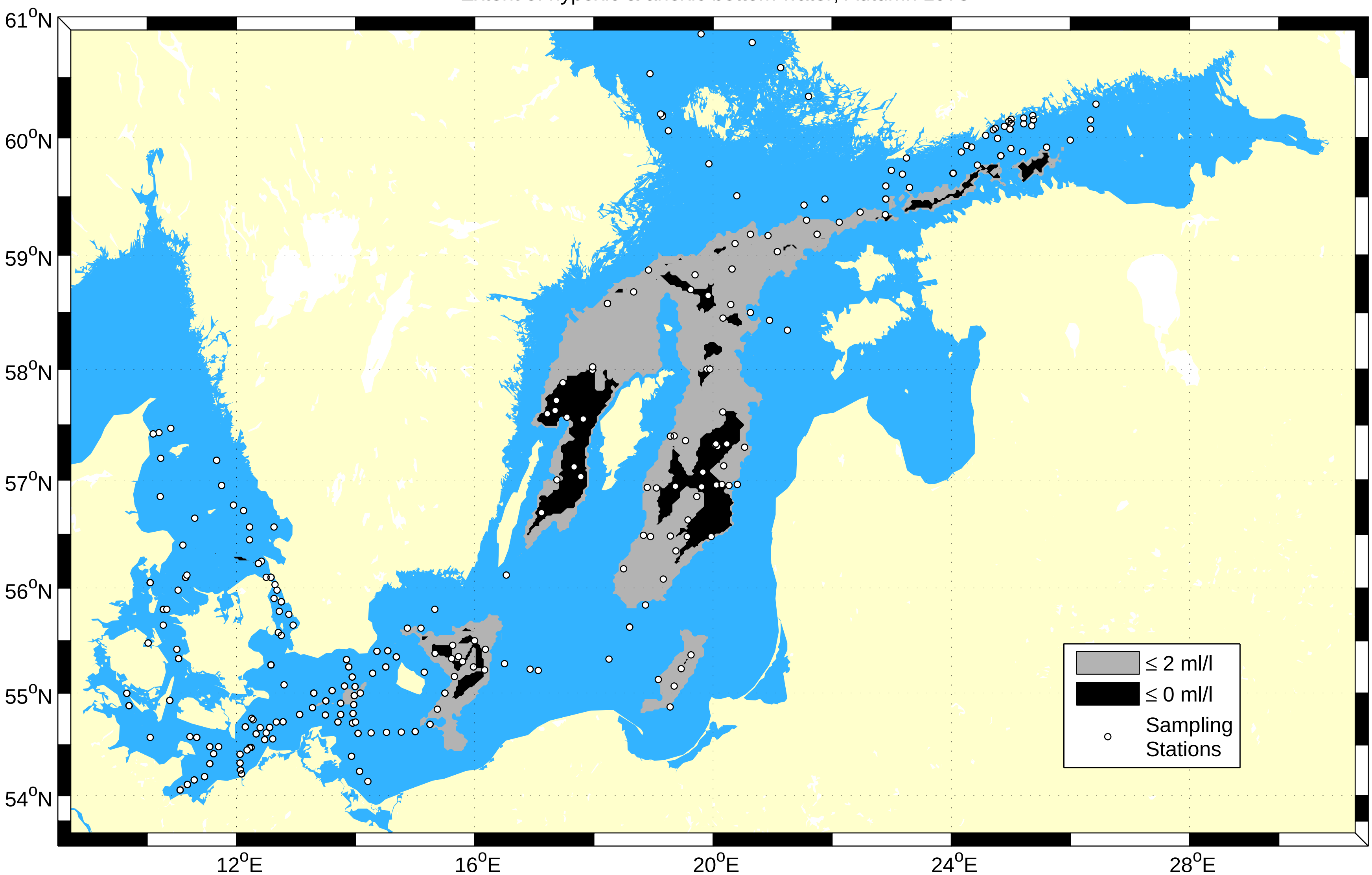
Extent of hypoxic & anoxic bottom water, Autumn 1980



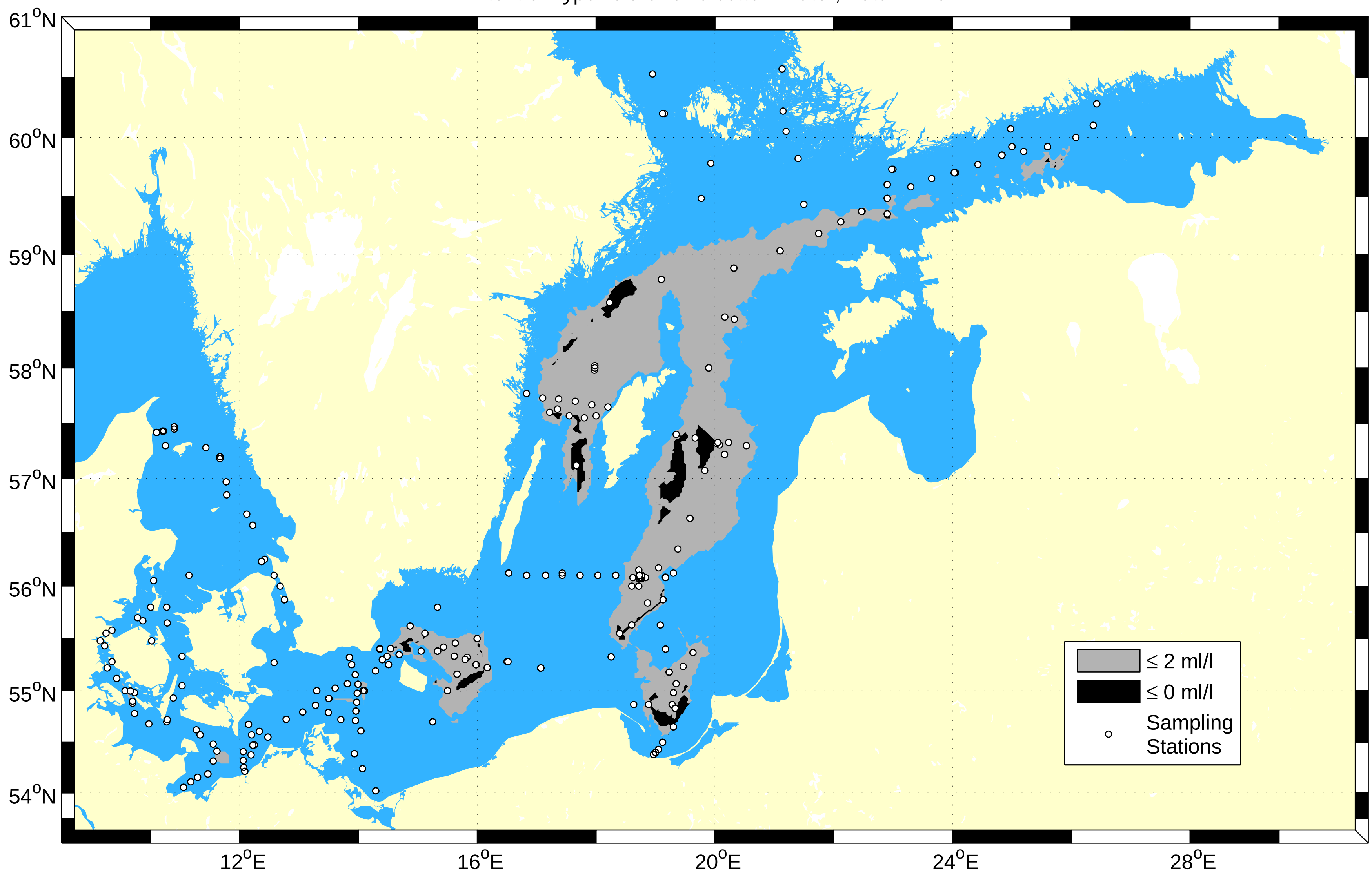
Extent of hypoxic & anoxic bottom water, Autumn 1979



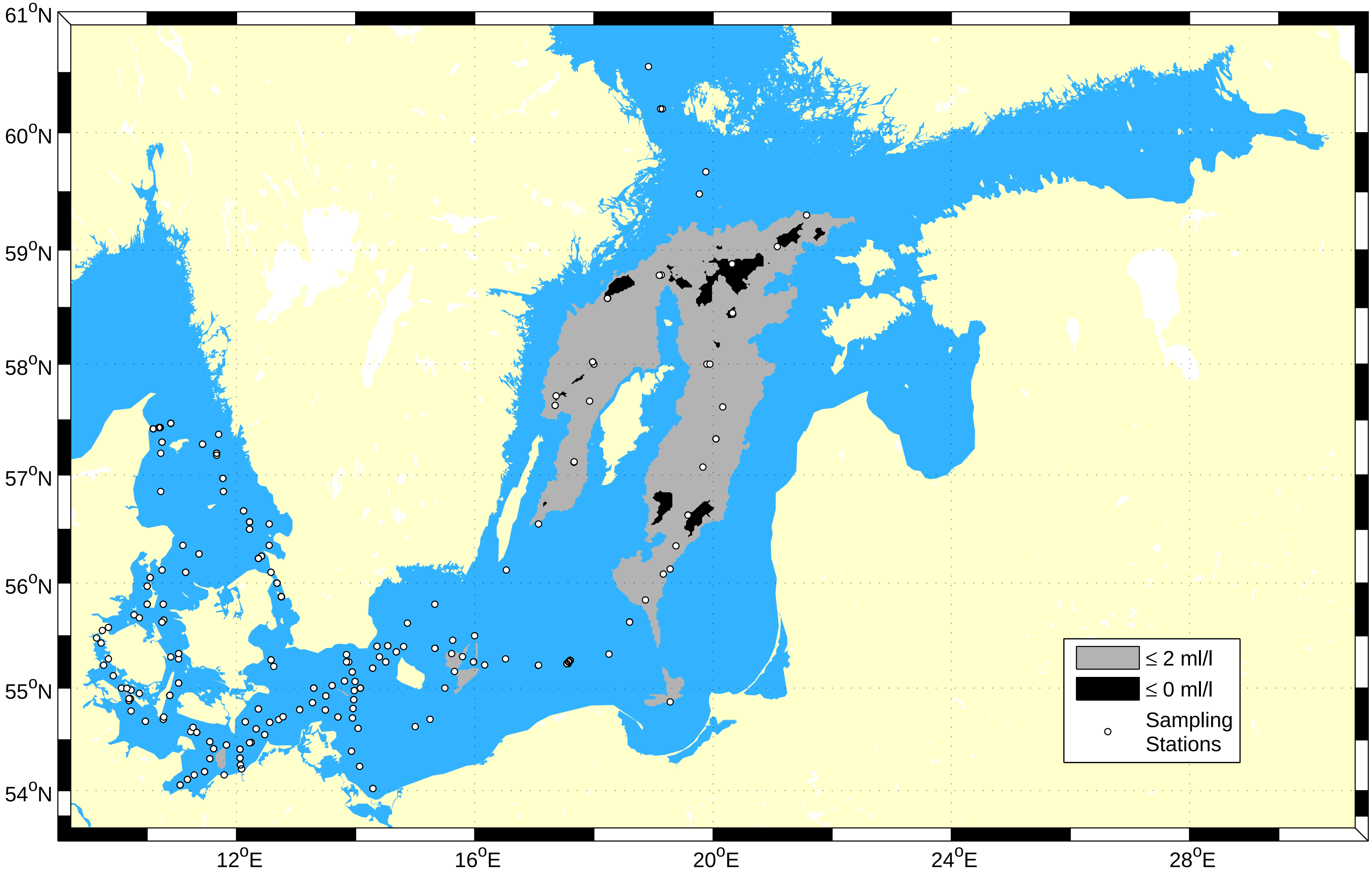
Extent of hypoxic & anoxic bottom water, Autumn 1978



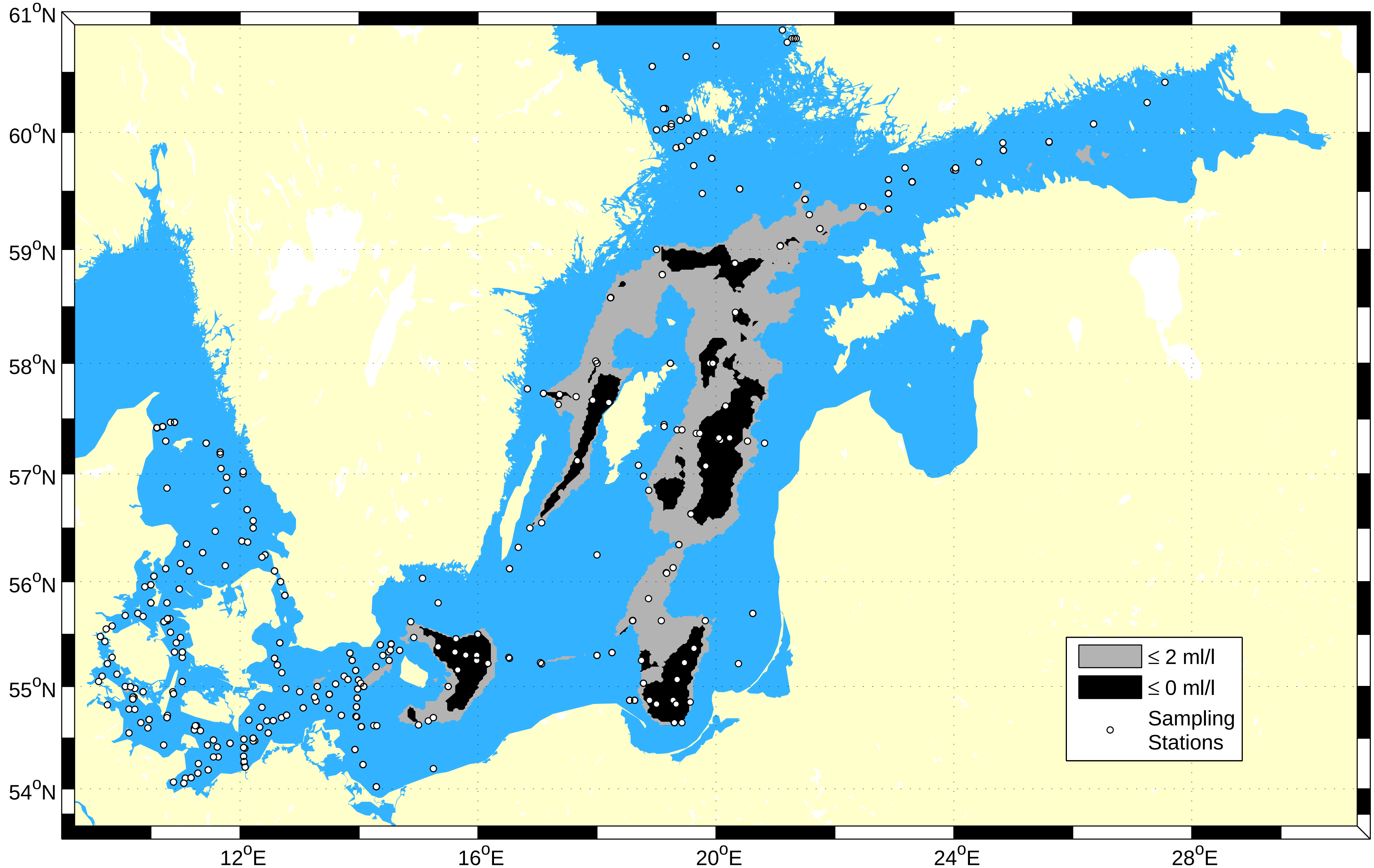
Extent of hypoxic & anoxic bottom water, Autumn 1977



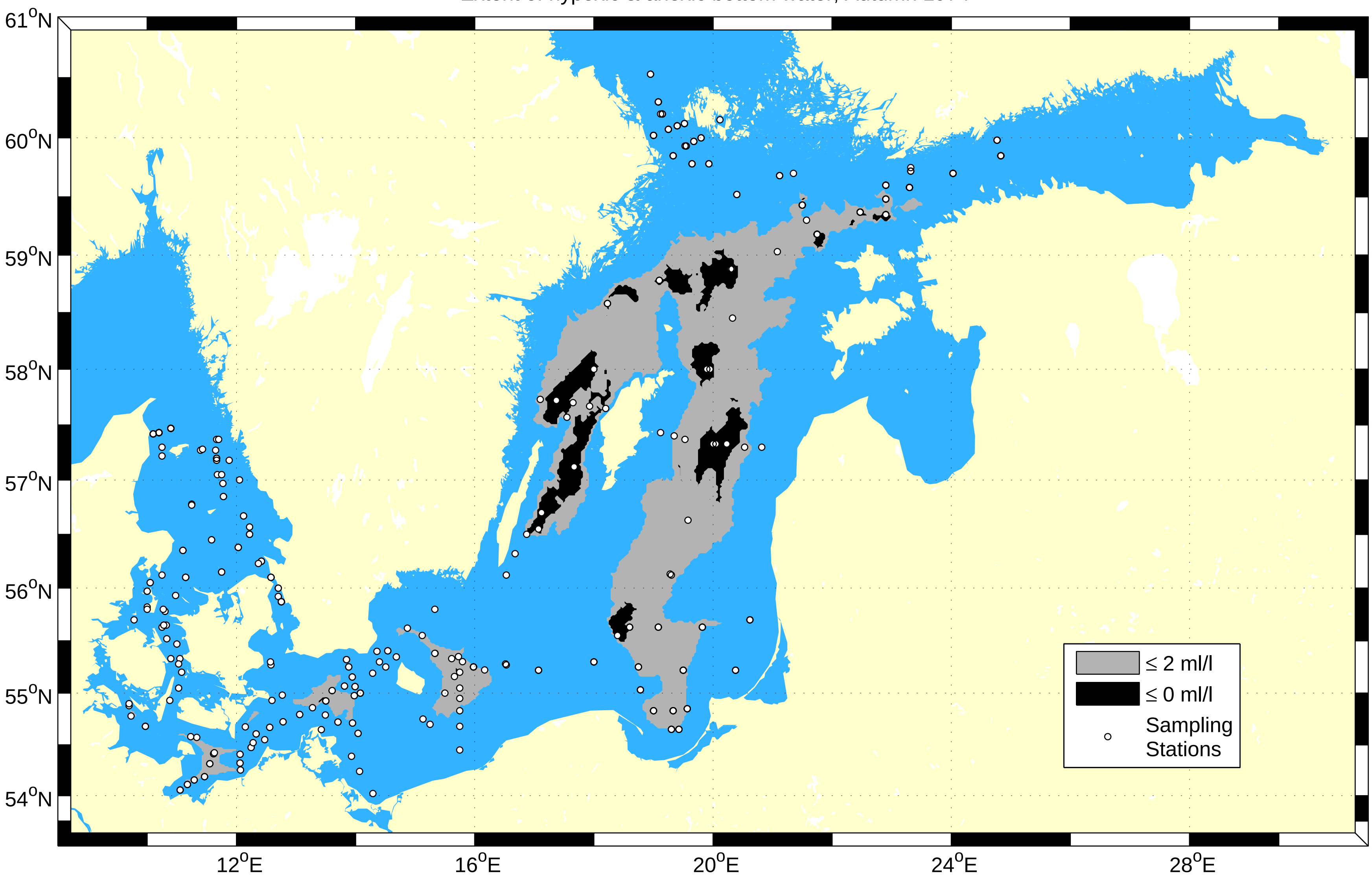
Extent of hypoxic & anoxic bottom water, Autumn 1976



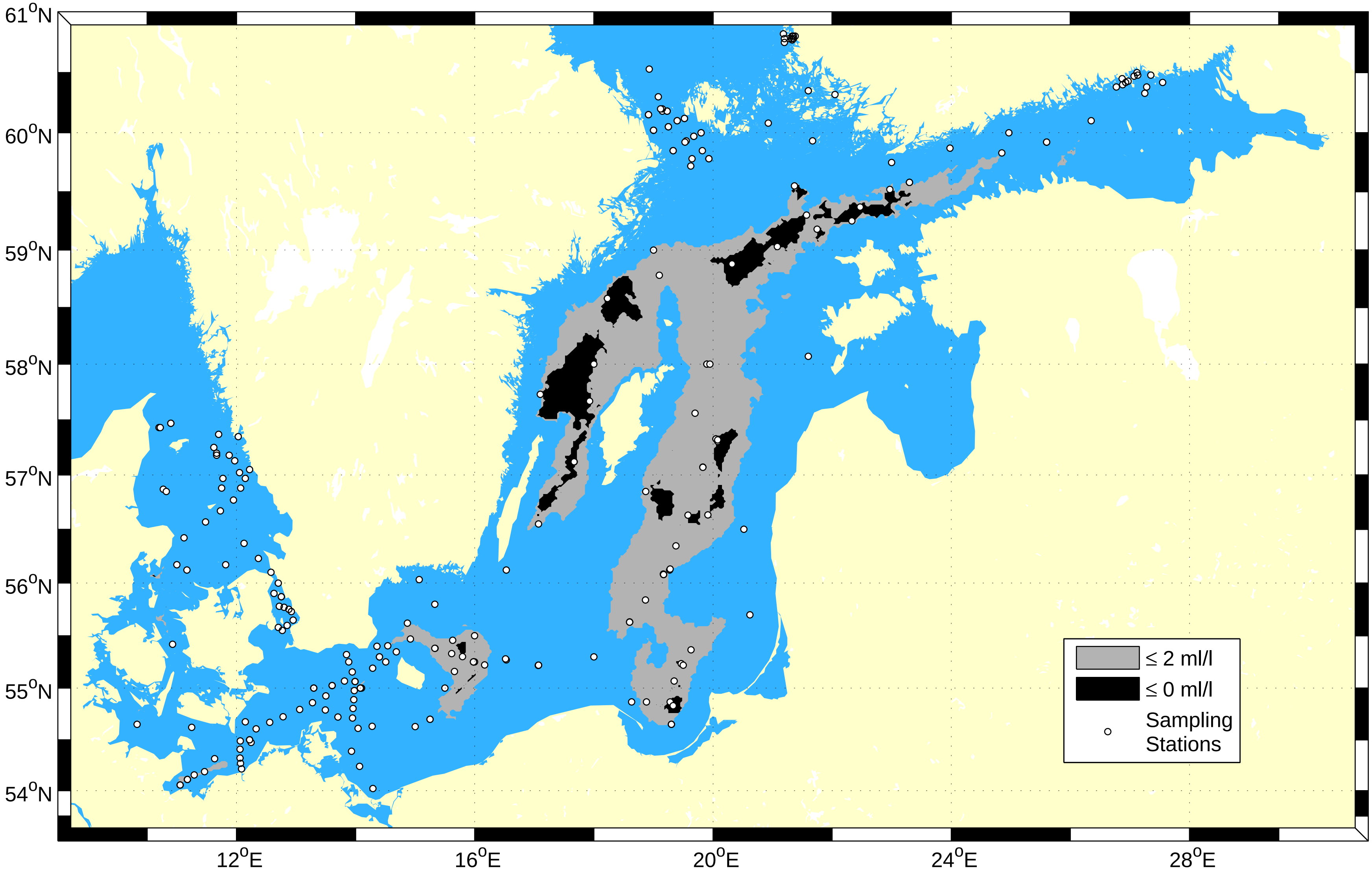
Extent of hypoxic & anoxic bottom water, Autumn 1975

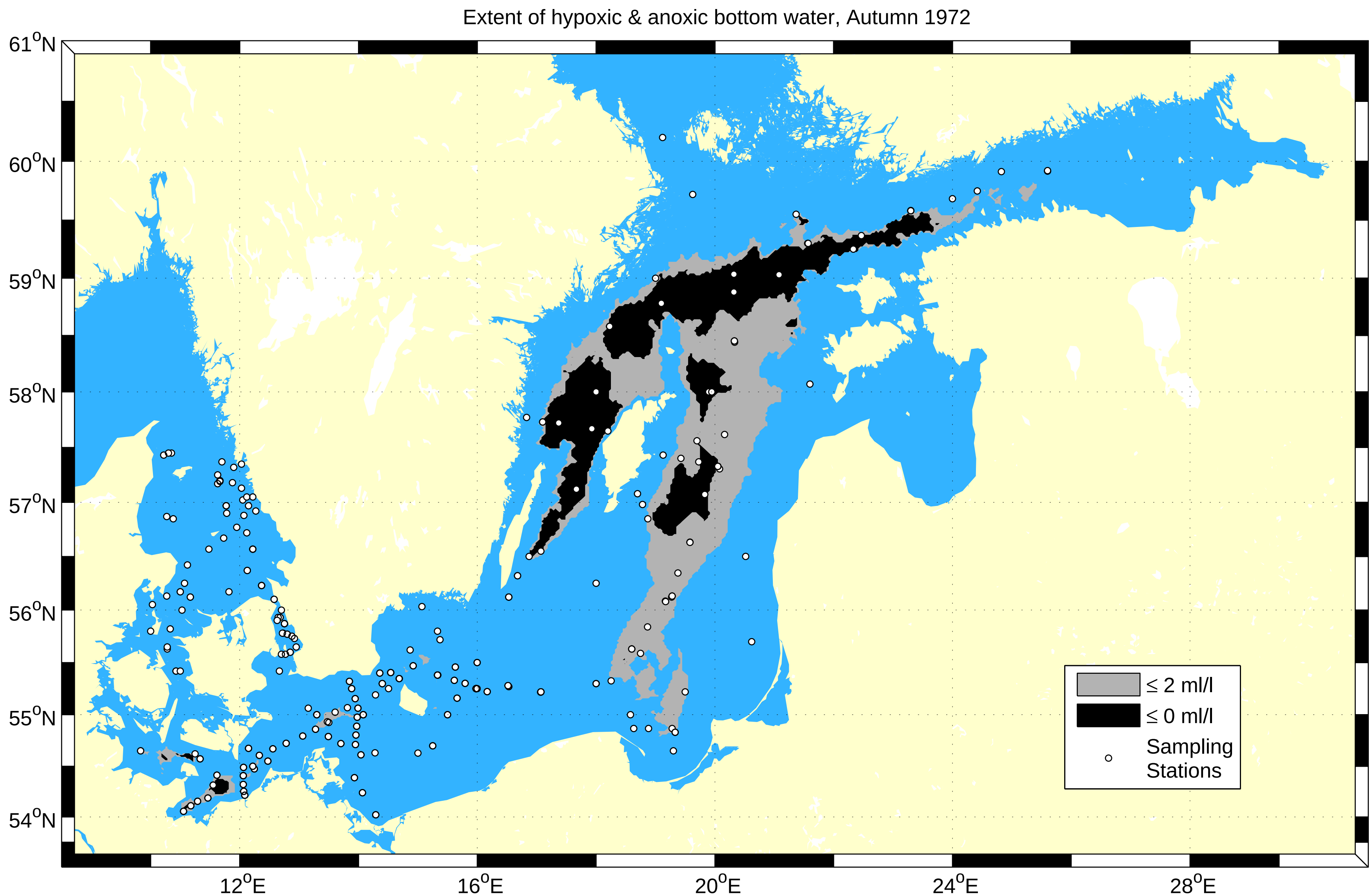


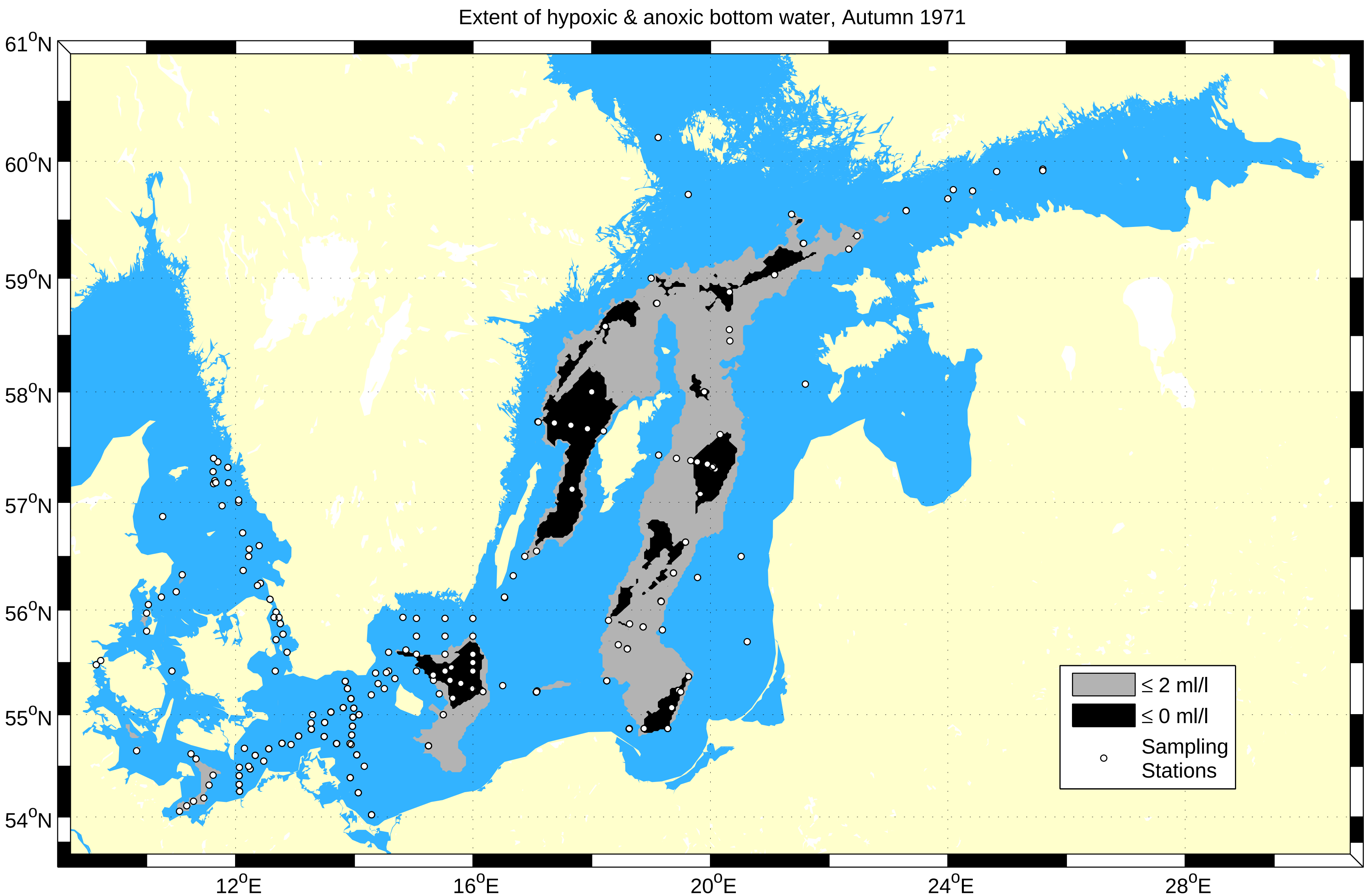
Extent of hypoxic & anoxic bottom water, Autumn 1974



Extent of hypoxic & anoxic bottom water, Autumn 1973

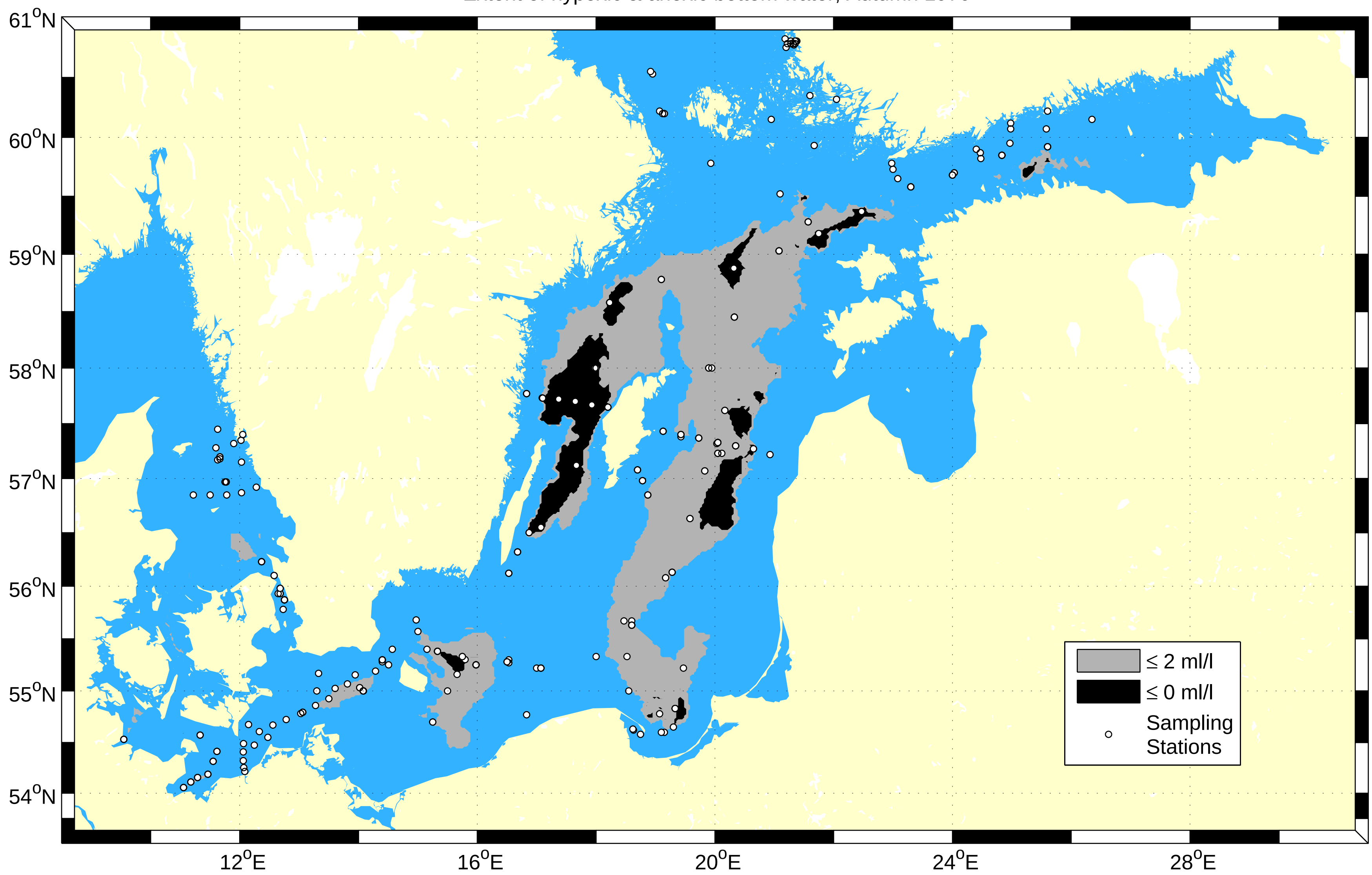



Extent of hypoxic & anoxic bottom water, Autumn 1972
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

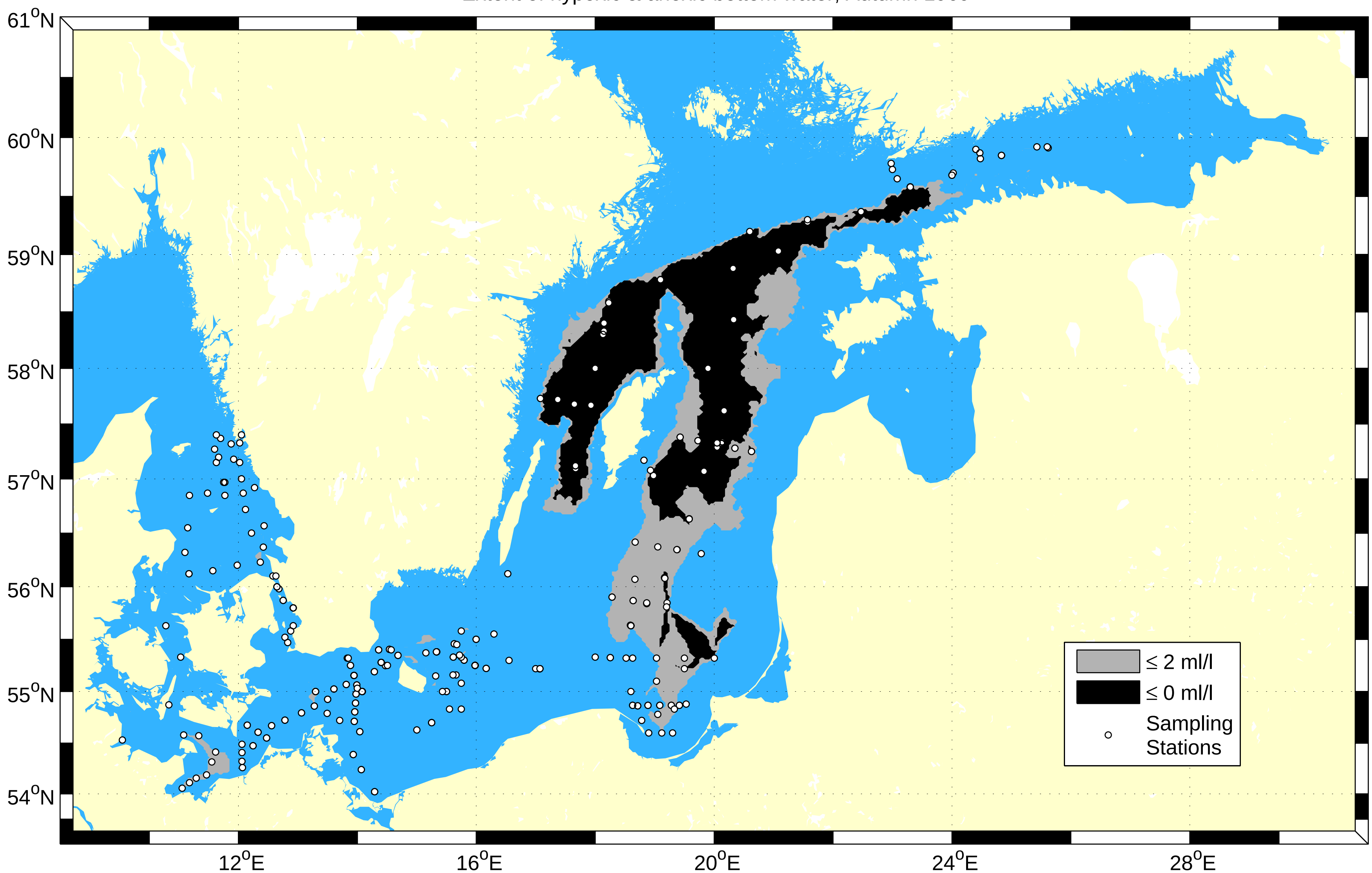


Extent of hypoxic & anoxic bottom water, Autumn 1971
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

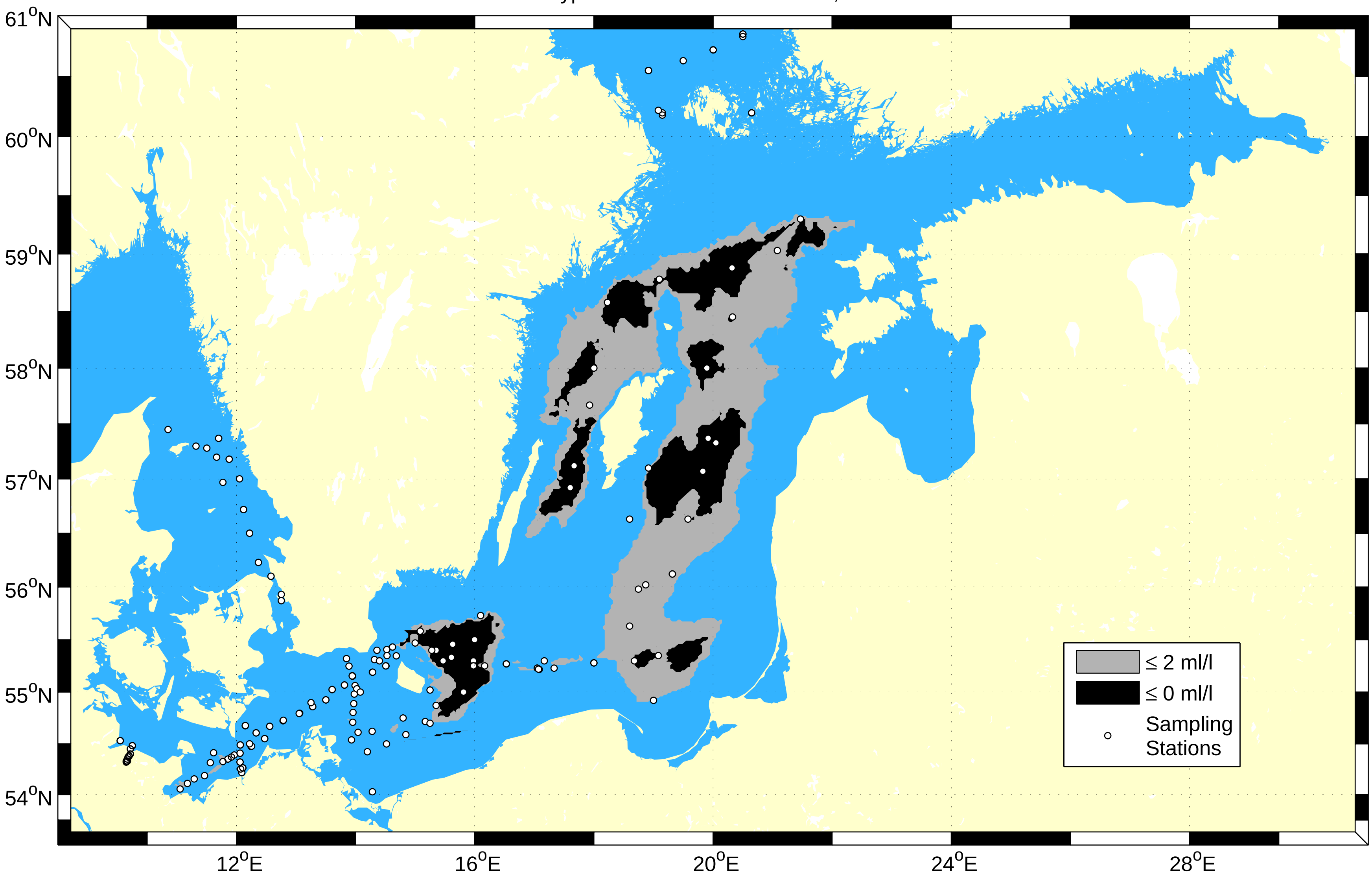
Extent of hypoxic & anoxic bottom water, Autumn 1970



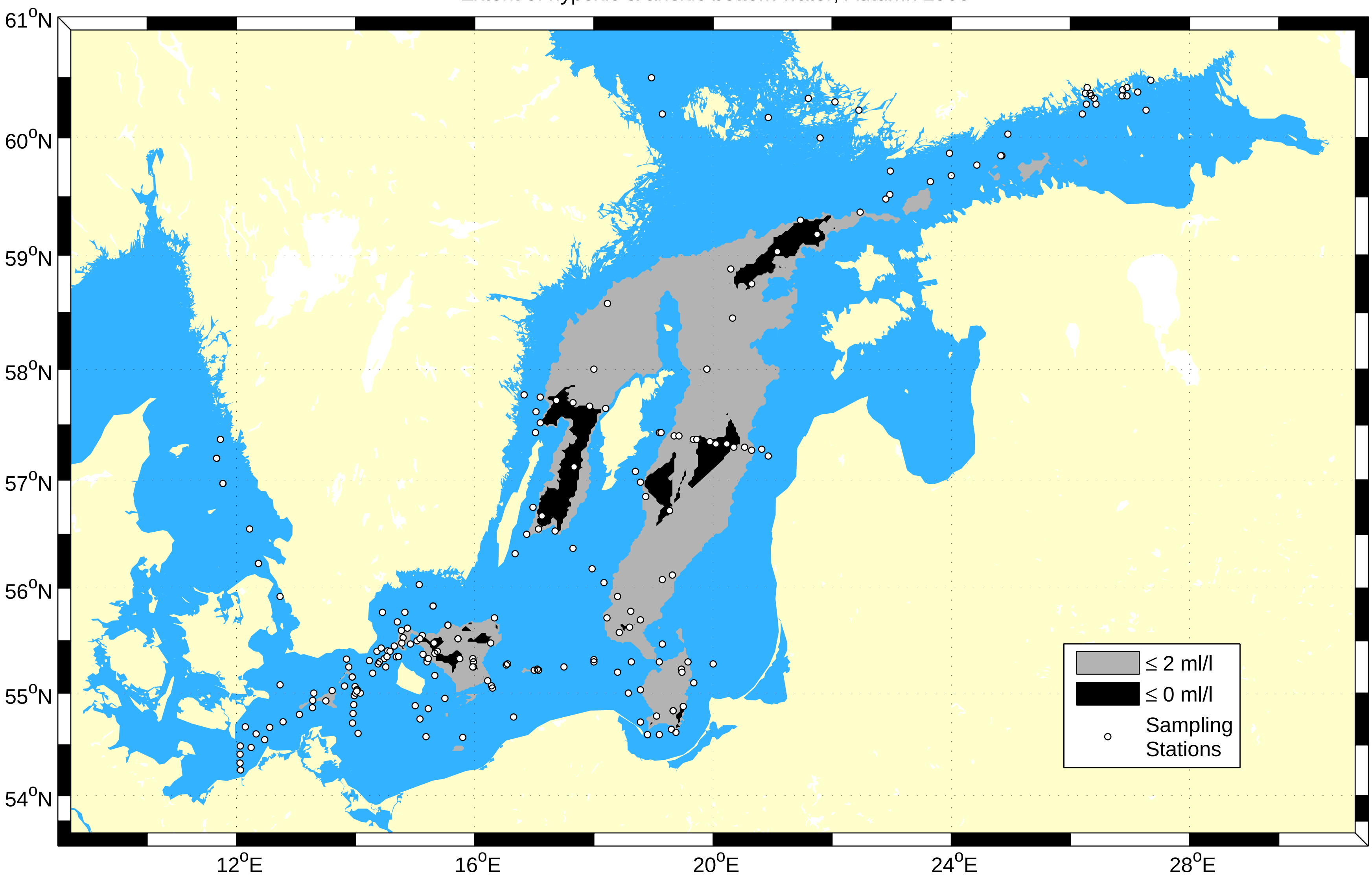
Extent of hypoxic & anoxic bottom water, Autumn 1969



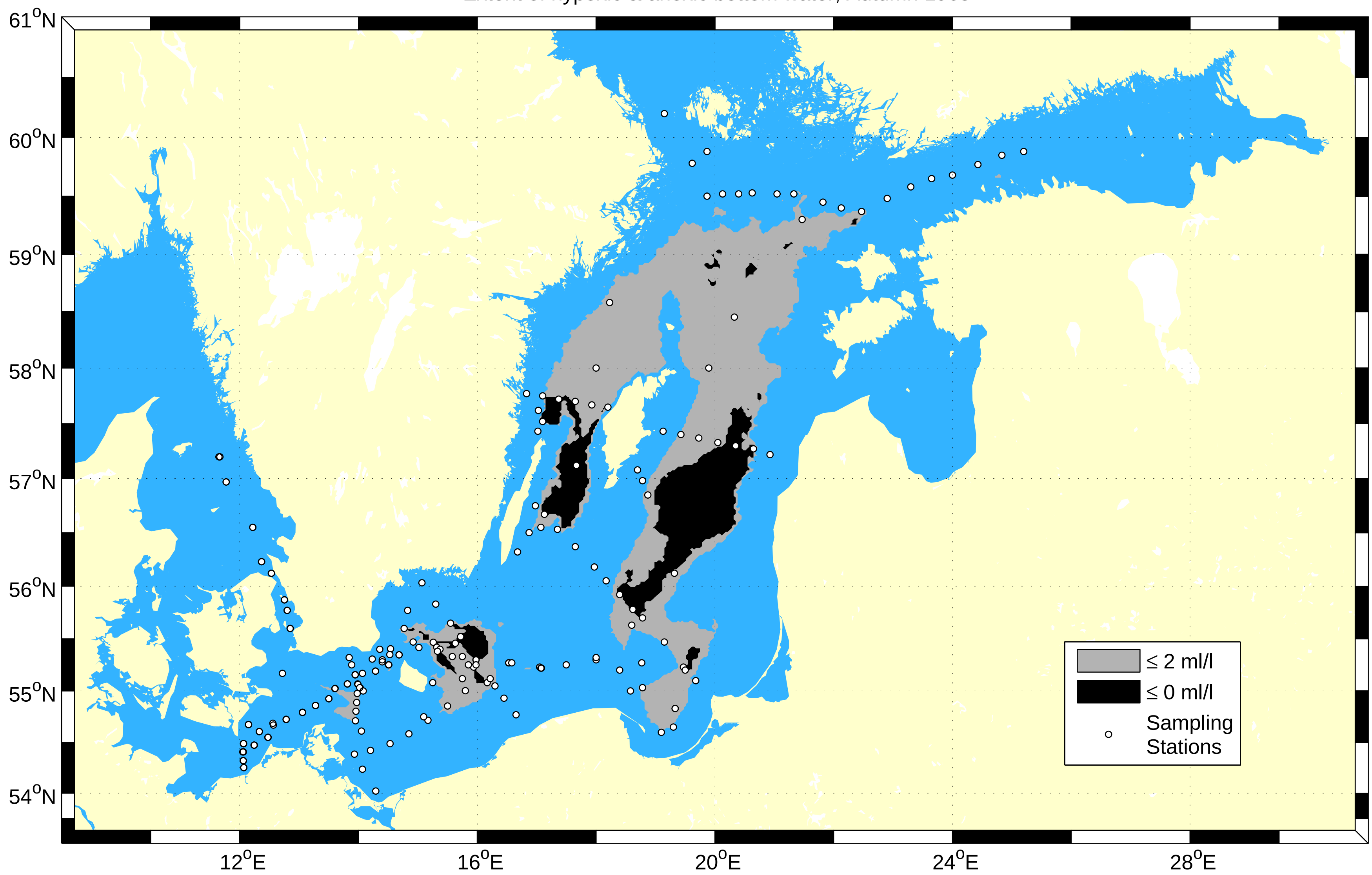
Extent of hypoxic & anoxic bottom water, Autumn 1968



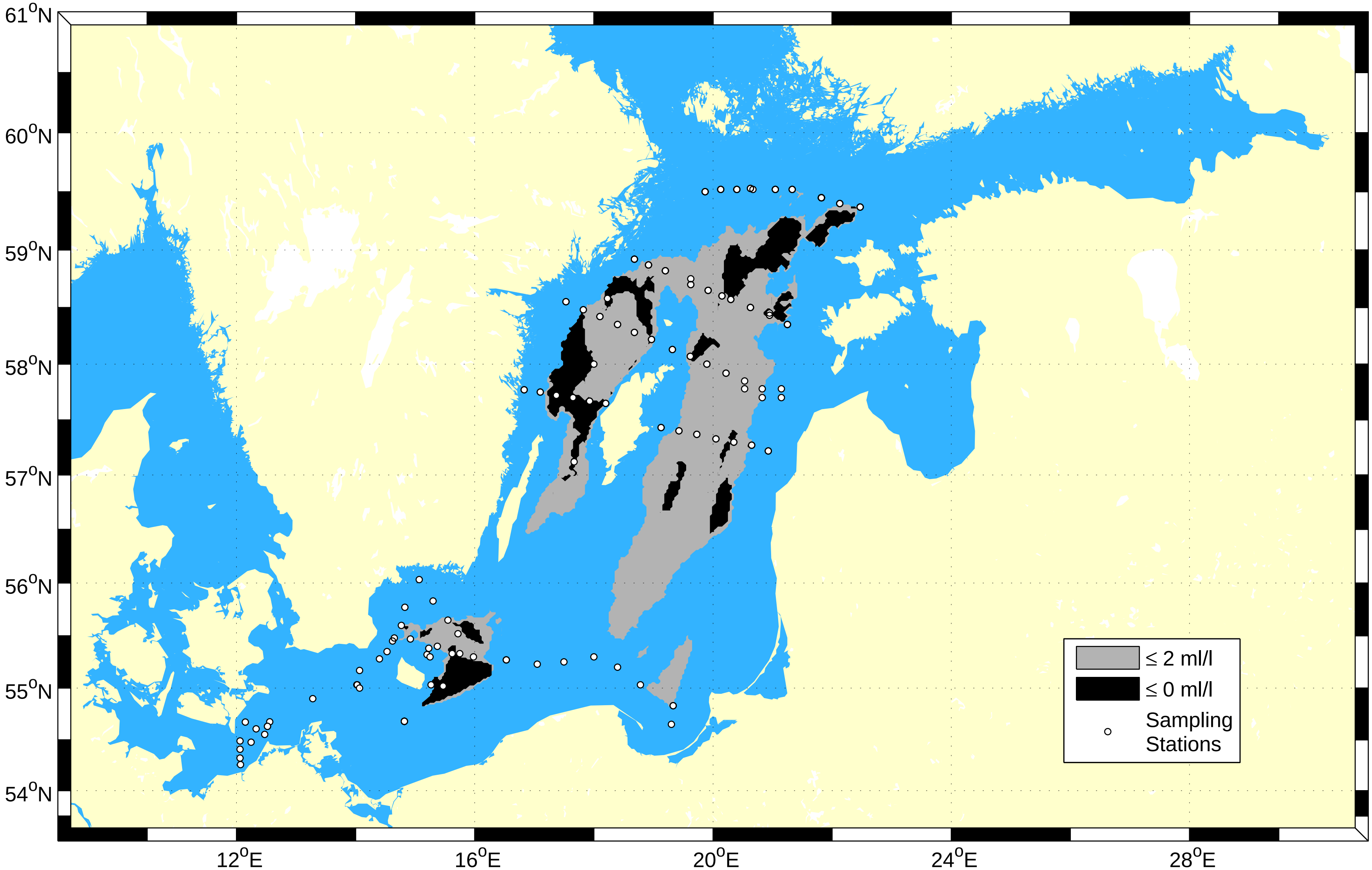
Extent of hypoxic & anoxic bottom water, Autumn 1966



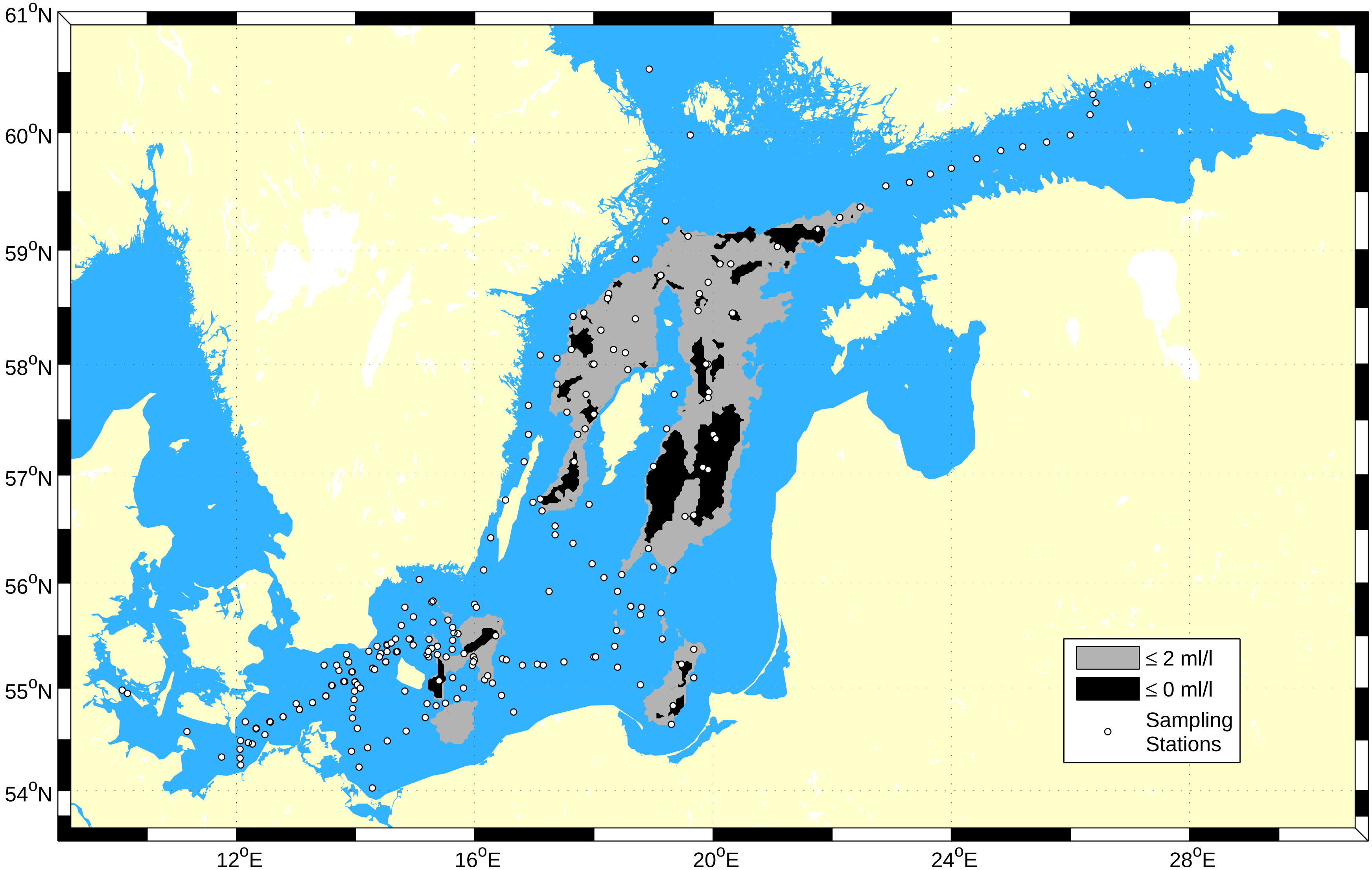
Extent of hypoxic & anoxic bottom water, Autumn 1965



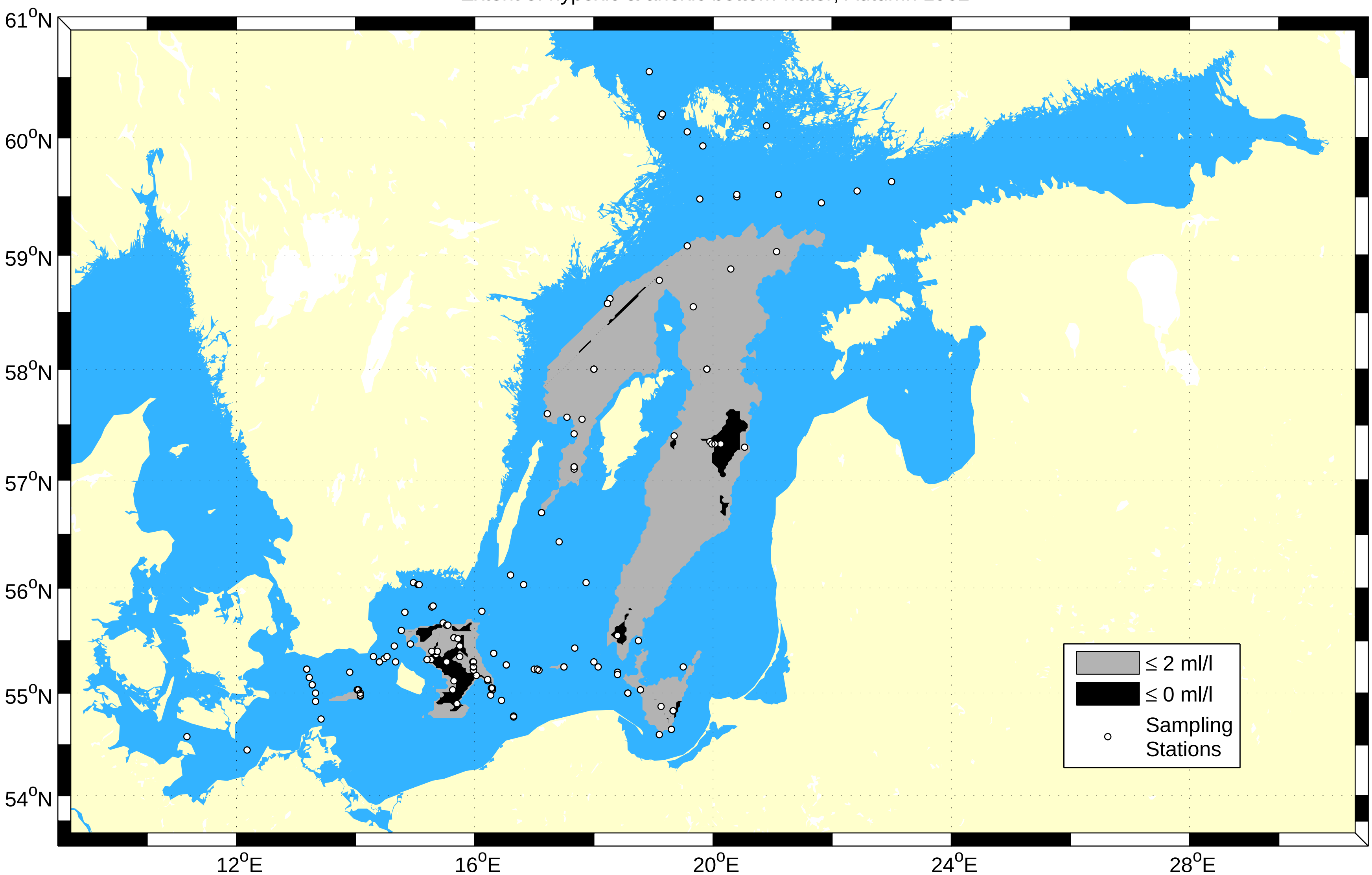
Extent of hypoxic & anoxic bottom water, Autumn 1964

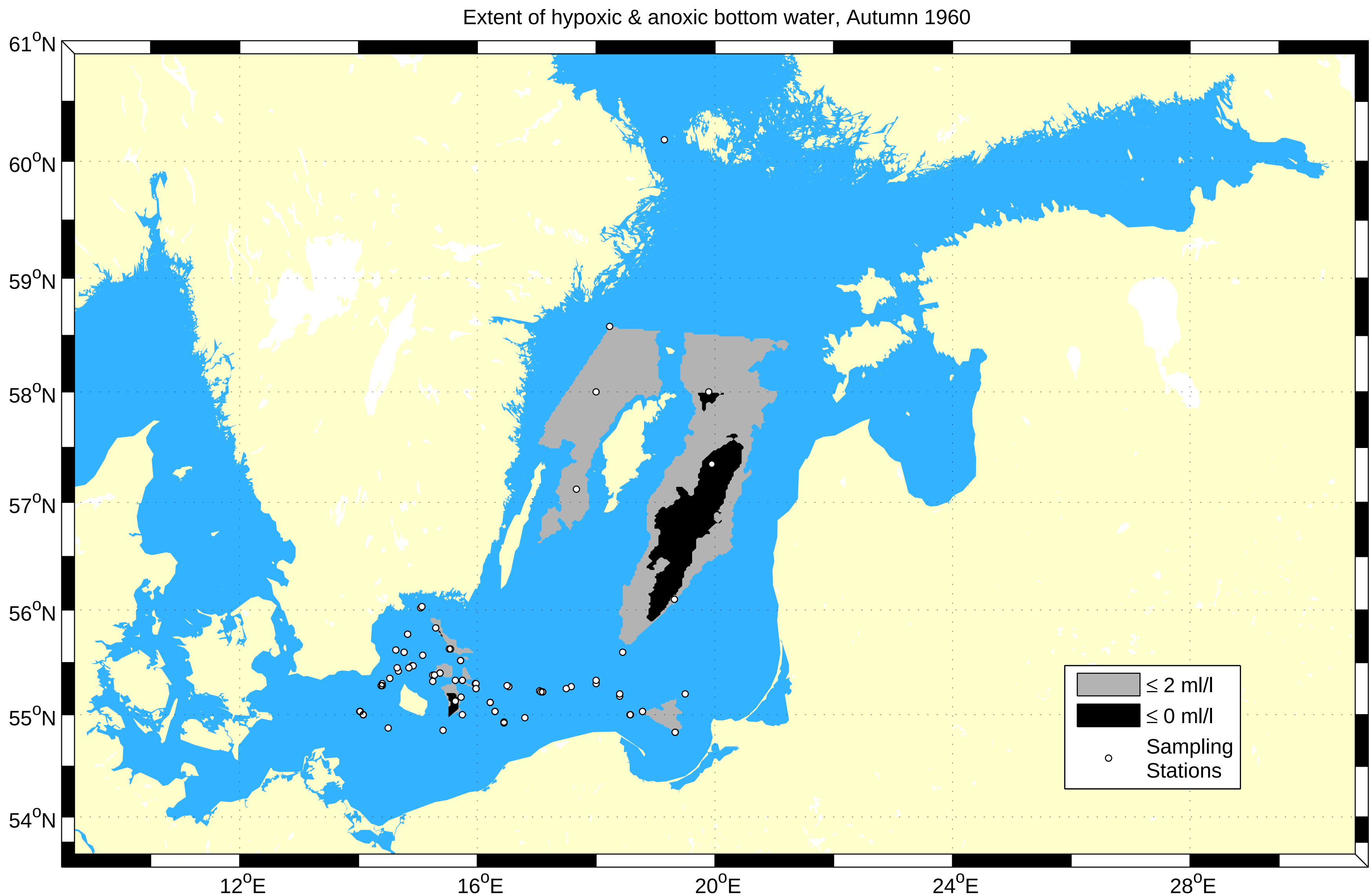


Extent of hypoxic & anoxic bottom water, Autumn 1963



Extent of hypoxic & anoxic bottom water, Autumn 1962




Extent of hypoxic & anoxic bottom water, Autumn 1960
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°E
16°E
20°E
24°E
28°E
≤ 2 ml/l
≤ 0 ml/l
Sampling Stations

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